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. Ms Kendall / 25015

MOBILE MULTIPLE ACCESS STUDY

FINAL REPORT

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AUGUST 16, 1977

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

TRW
DEFENSE AND SPACE SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH • CALIFORNIA 90278

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1. INTRODUCTION

Table 1-1 presents the basic requirements of the Mobile Multiple Access Communication System (MMACS) as gleaned from the study Statement of Work (Reference 1). The system will provide for personal communication between mobile terminals and from mobiles-to-base stations via a satellite repeater.

For example, the Public Service Communication System (PSCS) envisions a satellite system with Ku-band capability for large fixed ground stations and UHF capability to support a MMACS. This system is intended for government and public safety agencies, educational and medical groups, and other non-profit groups (References 2 and 3).

This study investigates multiple access techniques (FDMA, CDMA, TDMA) for the mobile user and attempts to identify the current "best" technique. Traffic loading is considered as well as voice and data modulation and spacecraft and system design. Emphasis is placed on developing mobile terminal cost estimates for the selected design. In addition, design examples are presented for the alternative techniques of multiple access in order to compare with the selected technique. The general constraints on the multiple-access system are:

- Low-cost user terminal
- High system capacity
- Simple mobile unit operation (e.g., no antenna pointing in mobile unit)
- Low development risk for spacecraft and terminals
- System flexibility and growth.

In addition, full CONUS coverage, mobile-mobile communication nationwide, and minimal probability of blocking is required.

Table 1-1. MMACS Requirements

Parameter	Specification
Number of Users	Hundred or thousands
Data Types	One or two voice channels, facsimile, low bit rate data
Terminal	Small, low cost
Operational Procedures	Simple, allows untrained user
Operation Region	Contiguous 48 states
User Terminal Channel	Either UHF (800 MHz) or L-band (1600 MHz)
Voice	Narrowband FM, 10 KHz bandwidth, overall carrier-to-noise density ratio at receiver terminal 47 dB-Hz
Facsimile	1200 or 2400 bps; bit energy-to-noise-density ratio of 8 dB (BER of 10^{-3})
Data	PCM-DPSK; 75 or 300 bps, bit energy-to-noise density ratio 10.3 dB, (BER of 10^{-5})
Service Modes	Transmit only, receive only, both transmit and receive (full duplex or half duplex)
Communication End Points	Both ends small terminal or one end central station
Terminal Types	Hand held, back pack, car mounted

Each mobile terminal employs a single channel for voice, data, or facsimile transmission with the signal characteristics listed in Table 1-1. Terminals may be receive only (e.g., paging or emergency broadcast), transmit only or both transmit and receive. Either full-duplex or half-duplex (push-to-talk) operation may be provided. The number of terminals is nominally 10,000, but may be lower at start-up or higher for a mature system. Terminal usage rates are assumed to be consistent with current mobile dispatcher networks (e.g., police, taxi cabs) and mobile radio point-to-point usage (e.g., industrial and government agencies).

In order to translate these general requirements into a system design, assumptions must be made regarding system utilization. A set of traffic models is examined in Section 3 and the number of multiple access channels is determined as a function of the number of user terminals.

In Section 4 the requirements of the various multiple-access systems (FDMA, TDMA, CDMA, SDMA) are considered and a selected multiple access technique is derived (FDMA). This technique is considered in detail in Section 5 and candidate system designs are developed.

The corresponding mobile terminal designs are developed in Section 6 to a block diagram level. This enables an estimate of parts costs to be derived. Options such as paging only, or data/facsimile interface are specifically considered. Other options may be examined by adding or subtracting the listed parts costs.

The manufacturing and production costs are derived in Section 7 as a function of the lot quantities produced. Assumptions concerning testing, quality control, and amortization of design costs are made here that are consistent with similar programs. The methodology of using volume production to lower unit costs is examined in detail for the types of terminals considered. Spacecraft cost and complexity are also discussed briefly.

2. EXECUTIVE SUMMARY

After a study of the advantages and disadvantages of CDMA, TDMA, SDMA and FDMA, the FDMA system was selected for the MMACS. The FDMA system

- Is compatible with existing mobile terminal equipment
- Results in most inexpensive and least complex terminal
- Accommodates a mixture of fixed assignment and demand-access terminals
- Would require very little new development
- Uses relatively simple spacecraft transponder.

The FDMA system design is relatively simple, yet with proper network control via order-wire or signalling channels it offers the potential for an efficient and flexible multiple access system. The selected FDMA system parameters are shown in Table 2-1.

Some of the disadvantages of the multiple-access techniques not chosen are:

- CDMA - very inefficient use of bandwidth
- TDMA - requires high-power transmitter in mobile unit
  - cannot accommodate a mix of less complicated units
  - ranging and synchronization required
- SDMA - not enough beams available at UHF and L-band from reasonable size antenna.

These factors were critical even for hybrid systems of the types FDMA-CDMA, FDMA-TDMA. The listed disadvantages ruled in favor of a pure FDMA system.

Table 2-1. FDMA System Parameters

Parameter	Value	Comments
Number of Channels	25/Time Zone (100 in CONUS)	Voice Channel Equivalents
Frequency	820 - 870 MHz	
Voice Modulation	NB FM	
RF Bandwidth	10 KHz	
Channel Spacing	25 KHz	
Carrier to Noise	48 dB-Hz	
Data-Facsimile Modulation	FSK (non-coherent)	
Channel Spacing	5 KHz	5 Data Channels per Voice Channel
Demand Assignment Signalling Channels	3/Time Zone	Uses 5 KHz Data Channel
Message Length	100 bits	
Signalling Method	Random Access	
Spacecraft Antenna	9.8m elliptical	8 Feeds (4 beams)
Spacecraft Power	32 watts/Time Zone	
Ground Terminal Antenna	Conical Coverage	Conical Spiral,or Cavity Backed Spiral
Ground Terminal G/T	-24 dB/^{o}K	Edge of Coverage
Ground RF Power	35 watts	
Number of Ground Terminals Supported	1200 to 10,000	Variable with Traffic Loading
Cost per Terminal*	$1,900	10,000 units produced

*Costs based on survey of production and parts costs for full-feature terminal with order-wire.

For maximum efficiency the MMACS should incorporate a control segment using dedicated random access order-wire channels. Each mobile unit with the required signalling capability can request a communication channel. A system control station assigns channels, establishes priority, and broadcasts housekeeping or emergency messages. Some mobile units also operate partially or totally in a fixed network assignment under the control of a local base station. These mobile units may not incorporate signalling capability. Thus the control structure allows for a mix of mobile units of varying degrees of complexity.

From a traffic analysis it was found that multiple access capacity with assumed traffic loads (less than 10 percent average continuous terminal usage) is between 1,200 and 10,000 terminals for a 72 voice channel system. The delay probability is less than 10 percent and delay times are reasonably short for the assumed traffic model.

The multiple-access system choice of FDMA was based on several factors. Considering the alternatives, a TDMA system with 20 users per frame and 35 watts equivalent voice channel continuous power requires about 700 watts from the mobile terminal to maintain E_b/N_o. The TDMA scheme also requires time synchronization via the order-wire channel with range measurement at the net control station. Besides the complexity of this scheme it is inefficient for low data rate users because of the guard time required. The TDMA scheme would not accommodate simple, low-cost terminals without synchronization, nor would it be easily expandable once the timing, frame length, and other parameters had been established. The major arguments for TDMA are: (1) use of a saturated power amplifier in the spacecraft without intermodulation, thereby increasing capacity, and (2) demultiplexing/multiplexing of trunk-type signals in the spacecraft ("switchboard in the sky"). The first objective, however, requires increased uplink power, corresponding to the TDMA burst rate increase over the actual data rate. The second objective is of course not applicable to the mobile traffic assumptions.

Turning to CDMA, the major factor here is the enormous bandwidth required to overcome the cross-correlation noise from the other codes sharing the same channel. Only 13 simultaneous conversations require a minimum of 2 MHz bandwidth, for example (see Section 4.3). This compares with about 80 conversations supported in the same bandwidth by an FDMA system. At UHF or L-band the capacity of the CDMA system would be severely limited due to the relatively small spectral allocations to be expected in these bands. The advantages of CDMA are privacy, no intermodulation problem, and high flexibility in a point-point system with many points having different addresses.

Either of the digital systems (TDMA and CDMA) would require digital voice. The best choice for voice digitization appears to be 16 kbps delta-modulation along with noncoherent MSK carrier modulation. However, this requires slightly more carrier to noise ratio than analog narrowband frequency modulation (NBFM) and requires some increase in complexity.

The mobile unit with a more or less "omni" antenna sees a spread of about 1-3 ms in single pulse component arrival times due to multipath delays. This effectively limits the bit rate of a spread system (TDMA and CDMA) to less than 1 Mbps. Hence, the capacity of a pure TDMA or CDMA system is limited.

The UHF and L-band regions are each crowded and may not be available for the contemplated service. Mexico and Canada also object to "broadcast" signals impinging on their territory. However, assuming equal availability of each band the choice of UHF was made on the basis of about 6 dB better links, even assuming the same RF power at L-band. The antennas could be made smaller at L-band but the coverage and gain remains the same. L-band could make an eight-zone system a better candidate. Finally, UHF is now being used by landmobile systems (Chicago Bell Cellular Experiment) and equipment availability should not be a problem.

Use of Ku-band for base stations can be accomplished by the appropriate frequency translations within the spacecraft (assuming a Ku-band subsystem is already on the spacecraft). Impact on the UHF mobile system is approximately a doubling of capacity for a system with mostly mobile-base and base-mobile communication. There is no impact on the system design at UHF. The flexibility of such a technique for mobile-mobile communication is less and in this case the capacity increase would also be less.

The selected FDMA system envisions approximately 25 channels per time zone or a total of 100 channels to serve CONUS. Many of these channels could be pre-assigned to base-mobile networks along the lines of current systems, with relatively simple terminals and no requirement for order-wire capability. The bulk of the channels could then be "pooled" into a demand access system. System control is maintained by two or three order-wire data channels per zone connecting the users to a central station. The system controller responds to order-wire random-access requests from users, assigns channels, and monitors usage and broadcasts housekeeping data. Spacecraft design is relatively simple, consisting primarily of a "bent-pipe" transponder (with channel dropping and cross-strapping) along with a 4-beam antenna (9.8 meter elliptical aperture with 8 feeds). A user-to-user intra-zone or inter-zone connection (full-duplex or half-duplex) may be established. Certain channels are cross-strapped in the transponder to the same zone and others to alternate zones. Voice transmission (NBFM) on 25 kHz channels and data/facsimile and signalling (noncoherent FSK) on the 5 kHz channels is used. The indicated voice quality and bit error rates are achieved with these modulations.

Terminals in the FDMA scheme may have full capability or reduced capability, e.g., receive only, or fixed frequency assignment only. Either voice or data may be used, with FM (narrowband) modulation and discriminator demodulation for the voice and FSK for the data. The random access order-wire channel also uses the same FSK modulator. A digital frequency synthesizer keyed by the order-wire channel provides 100 channel frequen-

cies. Voice activated transmission at about 30 watts RF power is used with dual diversity conical spiral antennas (nonpointable) for the mobile unit and a pointable helix for the portable unit. The hand-held unit is a low-capability unit which would probably not use order-wire demand access.

Terminal block diagrams and subassembly configurations were developed in order to obtain parts costs. The results for present-day parts costs are about $1,200 for the "full-up" FDMA terminal, $1,600 for the TDMA and $1,600 for the CDMA. The simplified FDMA terminal (no order wire) parts cost is $900. The impact of portable versus mobile units is small. However, the hand-held unit cost may be prohibitive due to miniaturization. These costs are conservative based on an industry survey and experience with similar electronic parts.

Complete manufacturing costs (including parts and labor) of mobile terminal units without a detailed electrical design are very difficult to estimate. Comparable units vary in selling price from $23,000 for a military mobile radio produced in small quantity (Ref. 3b) to about $1,600 for a commercial land mobile unit (Ref. 3c). The cost of the selected mobile unit design was estimated based on subassembly estimated parts costs and the design and manufacturing cost amortized over 10,000 units. The average cost per unit estimated was $1,900 for the "full-up" FDMA mobile terminal. The TDMA and CDMA terminals are equivalent in complexity and cost and are about 30% more costly than the FDMA terminal (see Section 7 for full cost details). It is emphasized that these estimates are not firm quotations from vendors or based on detailed design manufacturing methods.

Recommended areas for further study are listed below:

<u>Technology</u>

- High-power low-noise ground units (30-35 watts). Miniaturization of hand-held units
- Custom design and assembly for low-cost units
- Mobile unit directional antenna, either a small electronically-steered array or a mechanical pointing assembly (not absolutely necessary for selected system)

- Large four or eight beam UHF antenna (35 foot diameter for four beams)
- Narrow bandpass filters (25 kHz) in transponder
- High-power linear amplifier (16 watts or 32 watts per feed RF power)
- Automated system control demand access equipment (ground computer, mobile terminal signalling, and logic).

Engineering Design

- Control and signalling system design. Queueing, priority and access methods.
- Multipath and manmade noise into mobile terminal "omni" antenna.
- Passive intermodulation from strong downlink sharing the same antenna with a weak uplink
- Active intermodulation caused by large number of carriers (25) sharing quasi-linear amplifier
- Multipaction due to high-power amplifier
- Privacy and position location techniques
- Use of higher frequency bands for mobile units (above 10 GHz)

3. TRAFFIC ANALYSIS

Let the number of available channels be N and the number of potential user terminals be T. The usage of each terminal is a function of its mission, availability (e.g., downtime due to maintenance, off-peak hours, nonusage, and other factors may lessen availability) and the ease of access to the system (an unreliable or inconvenient system discourages use). In Table 3-1 two types of traffic loadings are presented. These two types represent a fairly heavily loaded multiple access system and a more lightly loaded system. (Recall that the extremely frequently used systems e.g., public safety dispatcher networks, can be assigned to dedicated channels. These are discussed separately at the end of this section.)

Table 3-1. Assumed Traffic Loading

Parameter	Type	Value
"Conversations" per two-terminal pair	A	5
	B	2
Busy period	A, B	8 hr
Average length of a conversation	A	10 min
	B	3 min
Terminal usage rate	A	10%
	B	1.3%

The capacity of the multiple access system is measured by the number of terminals supported with a fixed probability of delay. Since there are many more terminals than available channels, there is always a nonzero probability that all channels will be busy at any given time. All connec-

tion requests made thereafter are placed in a queue by the system controller. These requests are served on a first-come, first-served basis as channels become available. The probability that all channels are busy when a demand-access request is made is called the "probability of delay". If N is the number of available channels and m is the number of users in the system, this probability can be expressed as

$$P_D = \sum_{m=N}^{\infty} \frac{(\beta H)^m}{m!} e^{-\beta H}$$

where β is the total system demand-access rate and H is the holding time per terminal. From the traffic loading model these are:

	"A"	"B"
β	0.00521T sec^{-1}	0.00208T sec^{-1}
H	600 sec	180 sec

where T is the number of terminals.

The number of teminals is shown in Figure 3-1 for delay probabilities of $P_D = 0.1$, and $P_D = 0.01$. From these curves 10,000 active terminals would require about 72 multiple access channels to provide service (half-duplex) at a rate of overload occurrence of 10 percent ($P_D = 0.1$) and nine more channels (81 channels total) to bring the overload occurrence rate down to one percent ($P_D = 0.01$). This assumes the lighter "B" loading of traffic. If the heavier "A" loading is assumed the number of terminals that can be supported drops to about 1,200.

It appears from the above analysis that between 1,200 and 10,000 user terminals (depending on usage) can be supported by 72 multiple access channels with delay probability $P_D = 0.1$.

The remaining 28 channels (total 100 channels in CONUS) can be dedicated to extremely frequently used systems, e.g., dispatcher networks. Each authorized network (a group of users, usually a base station and many

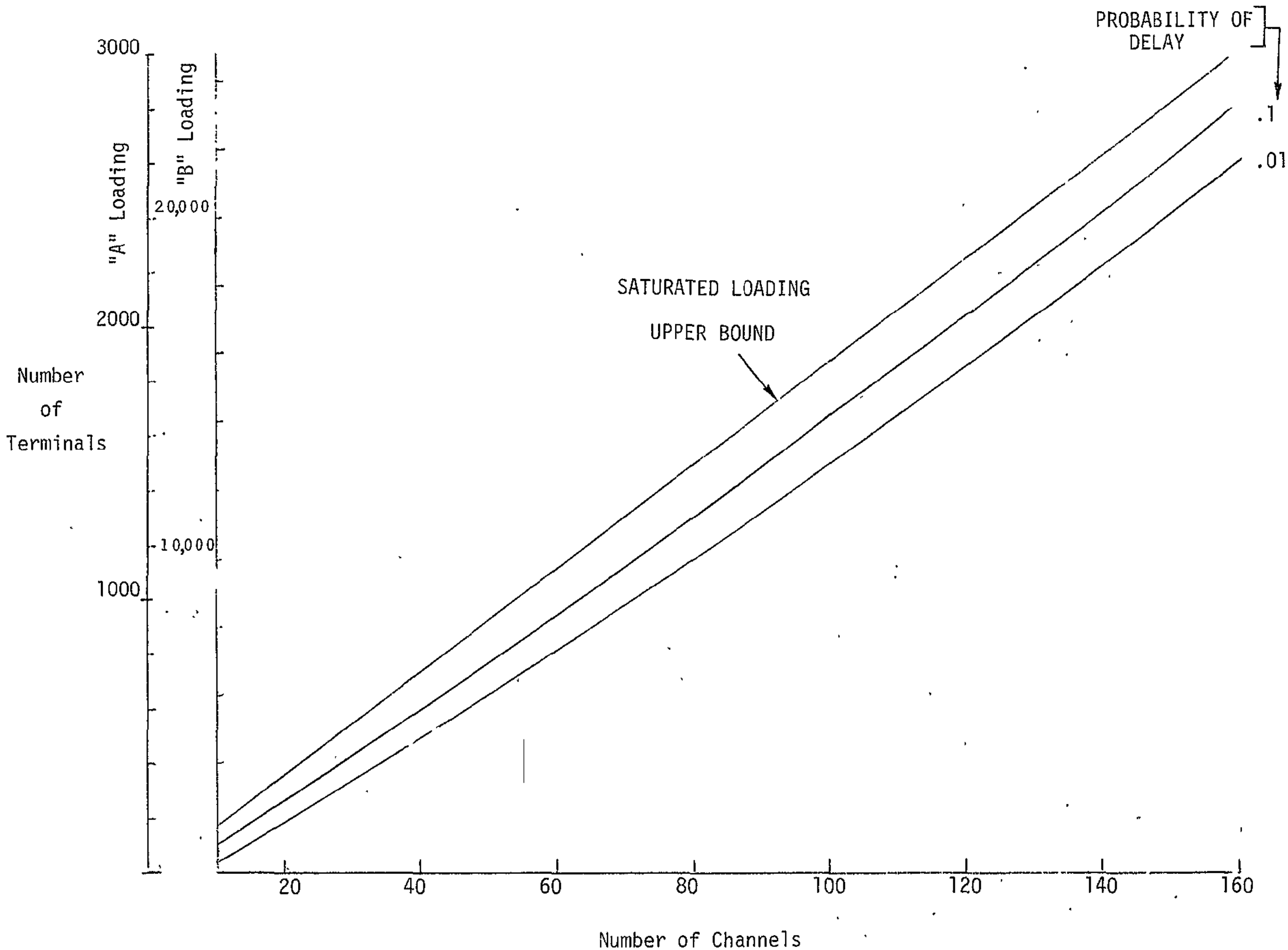

Figure 3-1. Number of Terminals versus Number of Available Channels (Traffic Loadings "A" and "B" are Defined in Text)

mobiles, but possibly a group of a few high-priority mobiles) is assigned one or more of these 28 channels (depending on its needs). These channels are exclusively reserved for terminals assigned to the network. Traffic control and network discipline is maintained by the network internally. Terminals within networks may still use the demand access channels if they have a need to "call" a terminal outside their own network and if they have the required order-wire and signalling capability. In Table 3-2 two types of traffic loading for the fixed assignment system are presented. The "C" loading represents one "call" every 5 minutes to or from each mobile unit in the network. The "D" loading represents one "call" every 10 minutes. In each case the total holding time for the mobile-base communication and acknowledgment is H = 10 sec. This represents very frequent usage by terminals, but very short message bursts. This would be typical of police emergency services.

Table 3-2. Fixed Assignment Traffic Loading

Parameter	Type	Value
"Calls" per mobile unit	C	12/hour
	D	6/hour
Average length of a call	C,D	10 sec
Terminal usage rate	C	3.3%
	D	1.7%

If two or more terminals in the same network attempt a call simultaneously a collision results. The probability of collision can be expressed as

$$P_C = 1 - e^{-\beta H} (1 + \beta H)$$

where H is defined above and β is as follows:

	"C"	"D"
β	$0.0033T\ sec^{-1}$	$0.0017T\ sec^{-1}$

where T is the number of terminals per network. Let the probability of collision be $P_c = 0.1$. Then the above equation yields the number of terminals per channel: T = 15 for the "C" loading and T = 30 for the lighter "D" loading. Therefore, with 28 channels available, the number of mobile terminals supported in the fixed-assignment system is 420 to 840 units, depending on the traffic load. This assumes 10% collision probability and is in addition to the 1200 to 10,000 terminals already in the demand-access system.

4. MULTIPLE ACCESS SYSTEM TRADEOFFS*

4.1 FREQUENCY DIVISION MULTIPLE ACCESS (FDMA)

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4.1.1 Channel Assignment

In an FDMA system each user is assigned to a frequency channel within the available frequency band. The channels are nonoverlapping and together with guard bands they occupy the total passband of the satellite transponder. Only one user at a time may transmit on a given channel.

There are several possible methods of assigning users to the channels. For example, a user, or set of users, may be assigned permanently to a channel, or set of channels (dedicated service). The users then determine individual access, either through a local network controller, or by random access to a clear channel in the dedicated set, or by some other means. This method is used by taxi cab fleets and police dispatchers.

Another method of assignment is to appoint a network controller with authority to assign a channel (if available) to a user on a first-come first-served basis, or perhaps on a priority basis. Requests for service can be transmitted at random over an order-wire channel, or the network controller can periodically solicit service requests. The latter scheme is called polling. Once a channel is assigned, it remains assigned until the user releases it or a higher-priority user requests service, if a priority system is being used. This method is more efficient than the dedicated service method. It is also more complex for users and requires a network controller.

The three types of signal that may request service are single-channel voice, data at 75 or 300 bps, and facsimile (data) at 1,200 or 2,400 bps. The baseband audio channel is about 3.1 kHz wide. It appears that the voice channel requires the most bandwidth of the three types of

*Sections 4.1 through 4.5 are partly extracted from Reference 4.

signals. For example, narrowband analog FM voice requires a minimum bandwidth of about 10 kHz.

In view of the different bandwidth requirements for voice and data the FDMA system would probably incorporate several types of channels that could fit in the same band as one voice channel.

4.1.2 FM Voice Modulation

The important voice channel parameters are bandwidth and output signal to noise ratio. For the special case of sinusoidal modulation and discriminator demodulation above threshold, the output signal-to-noise ratio is (Reference 5)

$$\left(\frac{S}{N}\right)_o = \frac{3}{2}\beta^2 \left(\frac{S}{N}\right)_i$$

where β is the modulation index and $(S/N)_i$ is the input signal to noise ratio. Thus, performance improves as the modulation index increases. On the other hand, the channel bandwidth is approximately

$$B = 2(\beta + 1)\ W$$

where W is the audio bandwidth. Therefore, the bandwidth also increases with β, and the number of channels accommodated decreases. For example, if $B = 10$ kHz as in the Statement of Work, and $W = 3.1$ kHz then the modulation index must be fairly small ($\beta = 0.61$). With an available carrier to noise density of 47 dB-Hz (input S/N = 7 dB) relatively poor performance would result (output S/N = 4.5 dB).

Output S/N is typically higher, however, in the case of voice-modulated FM. The threshold input S/N is shown in Figure 4-1 (Reference 6). For an RF bandwidth to voice bandwidth ratio of 10 kHz/3.1 kHz = 3.2 the threshold appears to be about 6 dB. (Similar thresholds would be obtained for a PLL.) The corresponding carrier to noise density at threshold is

$$\frac{C}{N_0} = 10 \log 10{,}000 + 6 = 46 \text{ dB - Hz}$$

The output signal to noise ratio is shown in Figure 4-2 for various bandwidth ratios (Reference 7). The slanted dashed line corresponds to the FM threshold. From this figure it appears that the output S/N is about 16.3 dB at threshold input S/N of 6 dB.

A threshold extension receiver may lower the threshold 3 dB or more. The FM feedback receiver and the PLL are the most common threshold receivers although there is almost an endless variety (References 8 and 9). One method (Bell Aerospace Adaptive NBFM) uses a nonlimited PLL whose bandwidth decreases for small signal power, thereby maintaining lock and avoiding some FM "click" noise (Reference 8). Threshold extension to 39 dB-Hz has been demonstrated. Further improvement can be obtained by using FM de-emphasis. Although de-emphasis distorts the high frequencies in the audio channel it is not severe since most audio energy is in the 300-800 Hz range.

4.1.3 Digital Modulation

Digital voice modulation techniques are also available. The most attractive for the mobile application at present appears to be continuously variable slope delta modulation (CVSDM). At 38.4 kbps, telephone quality voice channels can be obtained. For the 25 kHz mobile channel a 15 ~ 20 kbps encoder could be used. Intelligibility tests show that voice intelligibility is flat up to five percent bit error rate (see Figure 4-3). A spectrally narrow modulator such as MSK (Minimum Shift Keying) or QPSK would be preferred to regular PSK or DPSK. A 16 kbps encoder/decoder chip

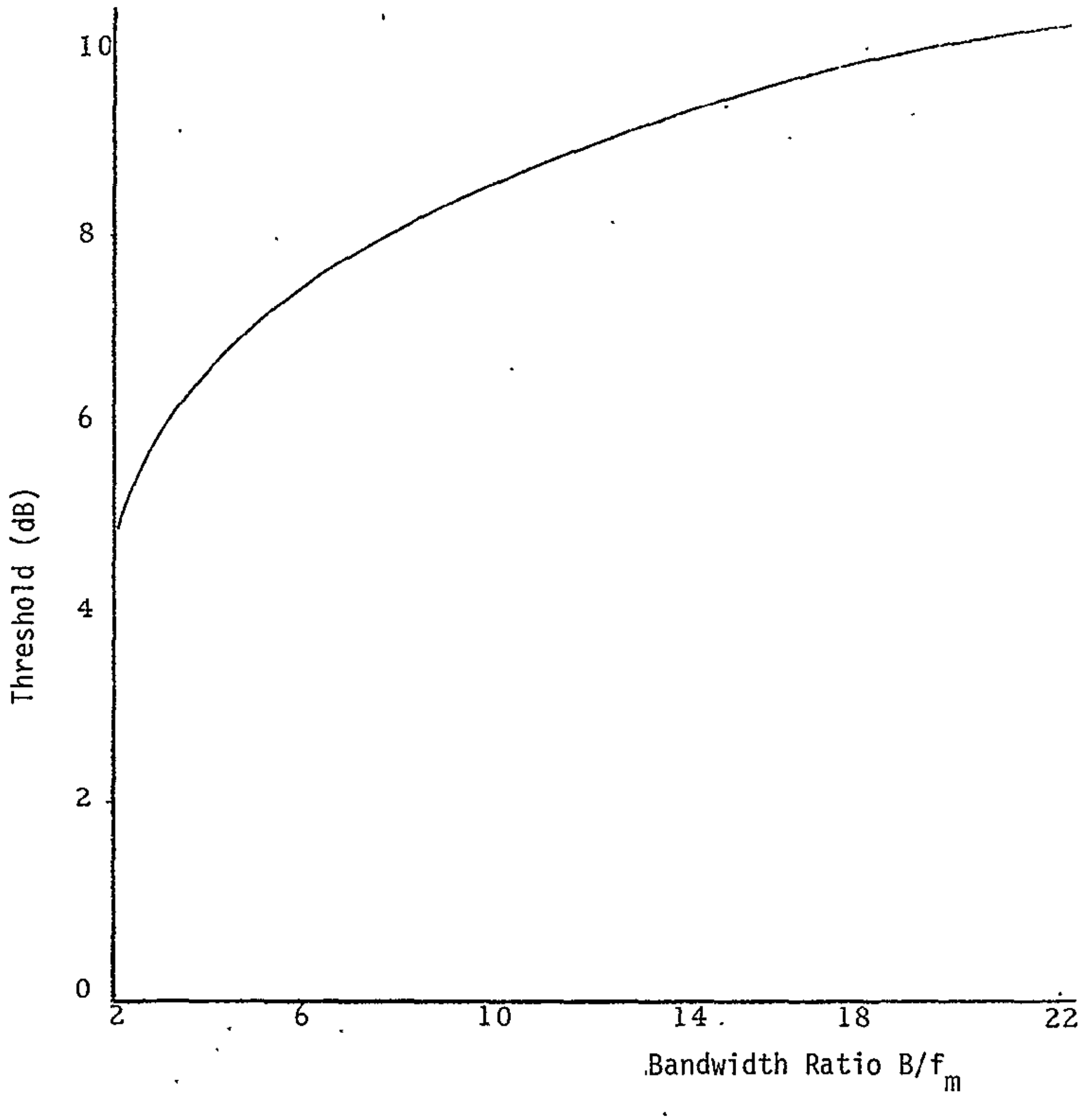


Figure 4-1. Threshold SNR for an Ideal Conventional Frequency Demodulator (Voice Modulation)

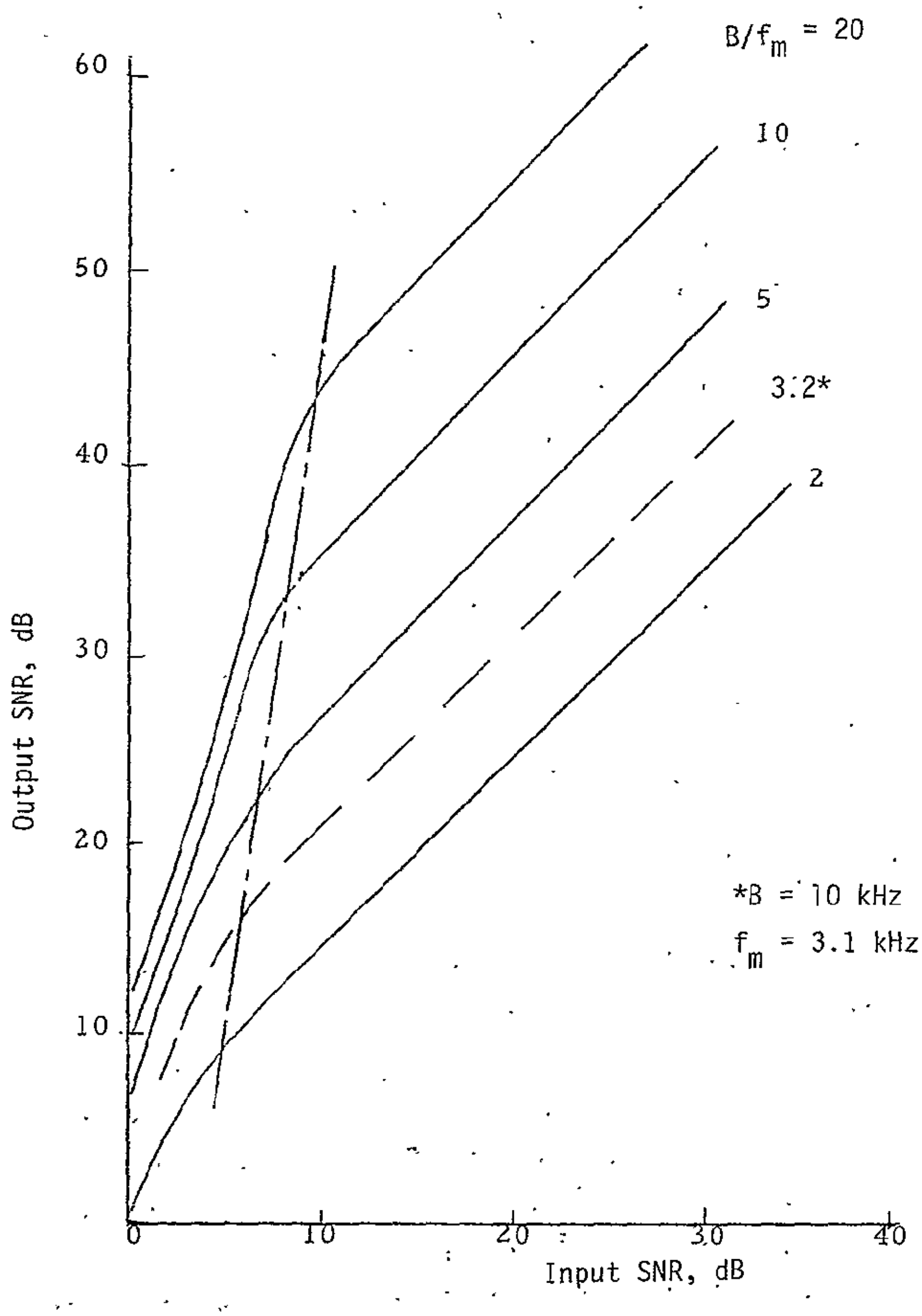


Figure 4-2. Output SNR versus Input SNR of a Frequency Modulated Signal (Voice Modulation)

is now available for CVSDM. The amount of out-of-band power for an MSK signal is shown in Figure 4-4. This is -23 dB for MSK whereas a QPSK signal is -13 dB at normalized one-sided bandwidth

$$FT = \frac{25{,}000}{2} \frac{1}{16{,}000} = 0.78$$

Unfortunately, the full performance of MSK is difficult to realize due to a cumbersome double-PLL carrier-derivation loop which is susceptable to false-lock for small bit rate signals. [However, a new single-loop technique may prevent false-lock and provide better acquisition. (Reference 10).] Noncoherent FSK demodulation of MSK could be used. This would require a S/N of about 6.5 dB at the CVSDM threshold BER of 5×10^{-2} (see the BER curve of Figure 4-5). The corresponding carrier to noise density threshold is

$$\frac{C}{N_0} = 10 \log 16{,}000 + 6.5 = 48.5 \text{ dB-Hz}$$

Thus, the digital voice for the mobile application appears to require about 48.5-46 = 2.5 dB more power than narrowband FM at threshold.

4.1.4 Amplifier Nonlinearity

The major problem with FDMA (either digital or analog) is that a satellite transponder produces cross products between individual channels. This is because the satellite TWT or transistor power amplifier is operated in a nonlinear mode to achieve reasonable power efficiency. These so-called intermodulation products are numerous and appear throughout the total band. In the worst case of a large number of adjacent channels in a hard-limiting repeater the noise power thus created is -7.8 dB at the band center and about -9.4 dB near the edges. This can be improved to about -10 dB and -11.5 dB if the spacing is made about two times the channel bandwidth although this solution is wasteful of bandwidth (Reference 12).

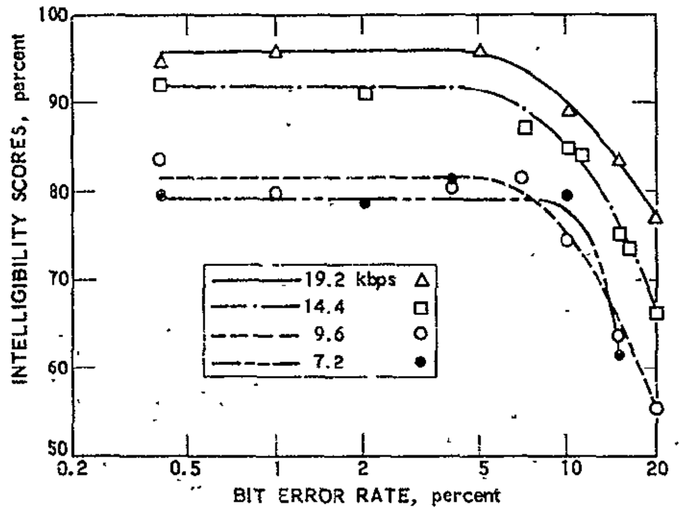


Figure 4-3. Intelligibility versus Bit Error Rate (Reference 11a)

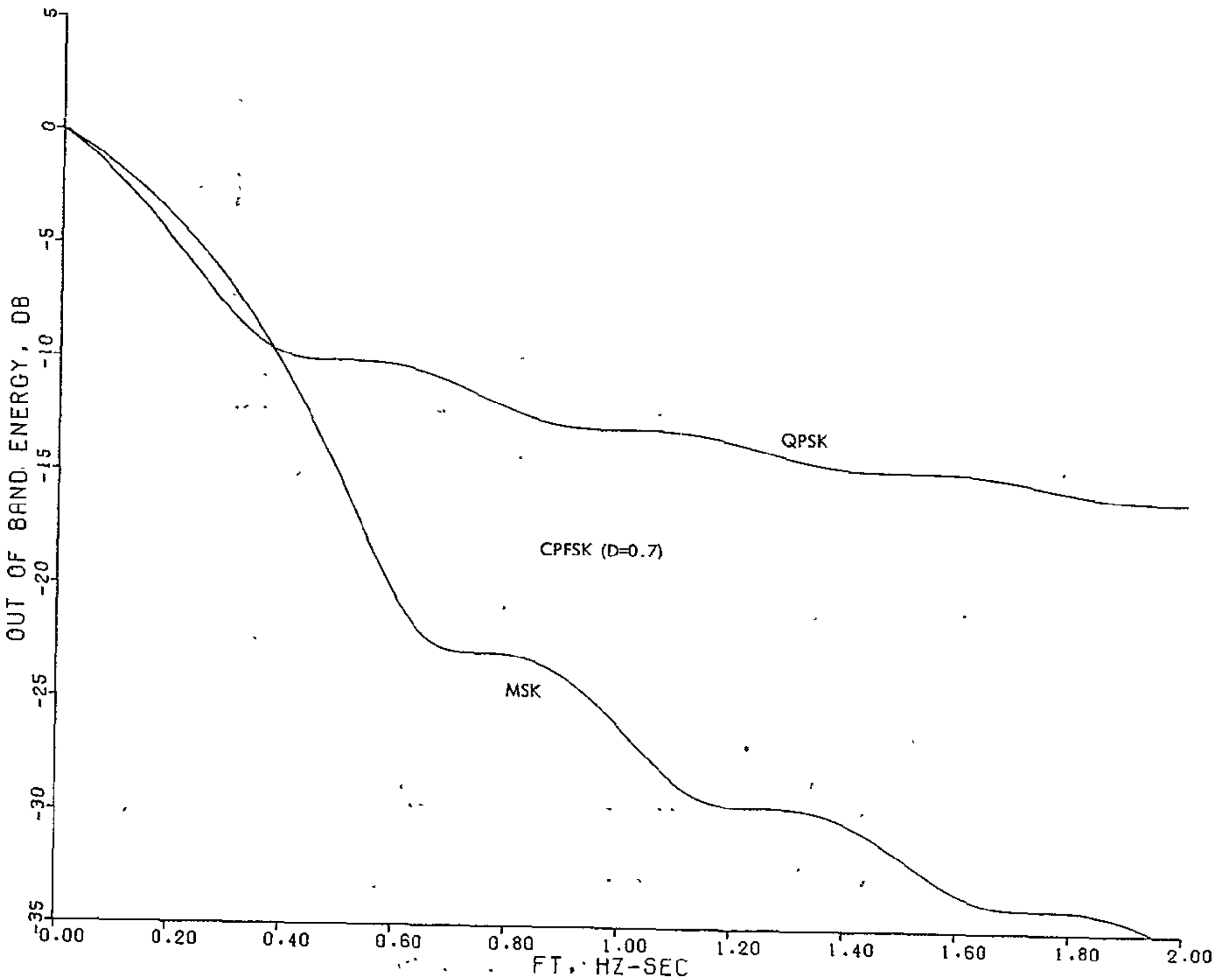


Figure 4-4. Relative Out-of-Band Energy (Reference 11b)

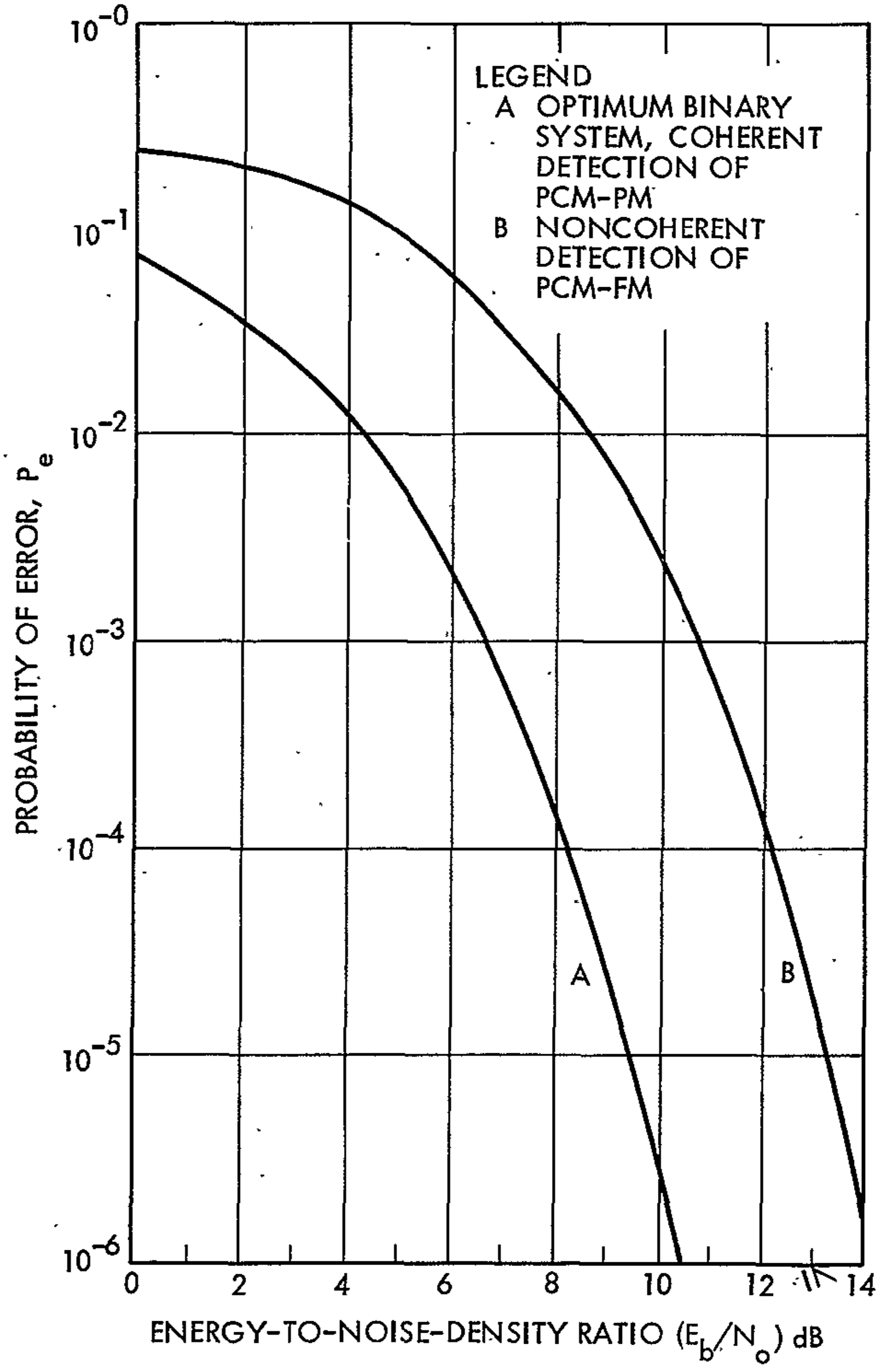


Figure 4-5. Probability of Error

The TWT or transistor may be backed off into a more linear region. Using a modified version of Berman's saturating characteristic (Reference 13) a computer program has been used to evaluate the individual IM levels and the number of IMs falling in each signal channel. A curve of the ratio C/IM is shown in Figure 4-6 for third and fifth order IMs where C/IM is the total carrier to intermodulation power at the center of the channel for a large number of equal carriers. From these curves it appears that a 5 dB output power backoff would yield C/IM $\approx$20 dB in the center signal channel (worst case). This backoff therefore would be adequate for achieving "quasi-linear" operation.

At UHF this method (quasi-linear operation) might require about 24 devices in parallel operating Class A to achieve in the neighborhood of 300 watts RF power. Such narrowband combining has been successful for up to eight devices and TRW is submitting a proposal now for the high-power amplifier (Reference 14).

4.1.5 Passive Intermodulation

The FDMA system is also susceptable to passive IMs arising in non-linear elements in the transmitter electrical path (e.g., switches, circulators, and antennas). For a strong downlink and weak uplink the high-order out-of-band IMs may override the received signal. This can be avoided by measurement of IM characteristics and allowing sufficient transmit and receive band separations. This is discussed in detail in Section 5 for the specific FDMA system parameters. It is also true that the same out-of-band noise is generated in the case of CDMA and TDMA with equivalent total bandwidth and power. Thus, passive IMPs (or their equivalent out-of-band noise) are equally a problem for all three multiple access systems.

4.2 TIME DIVISION MULTIPLE ACCESS (TDMA)

In a TDMA system each user only transmits during a prescribed time interval (called a time slot). The time slot may be assigned to the user permanently or for some fixed period after the user has requested an

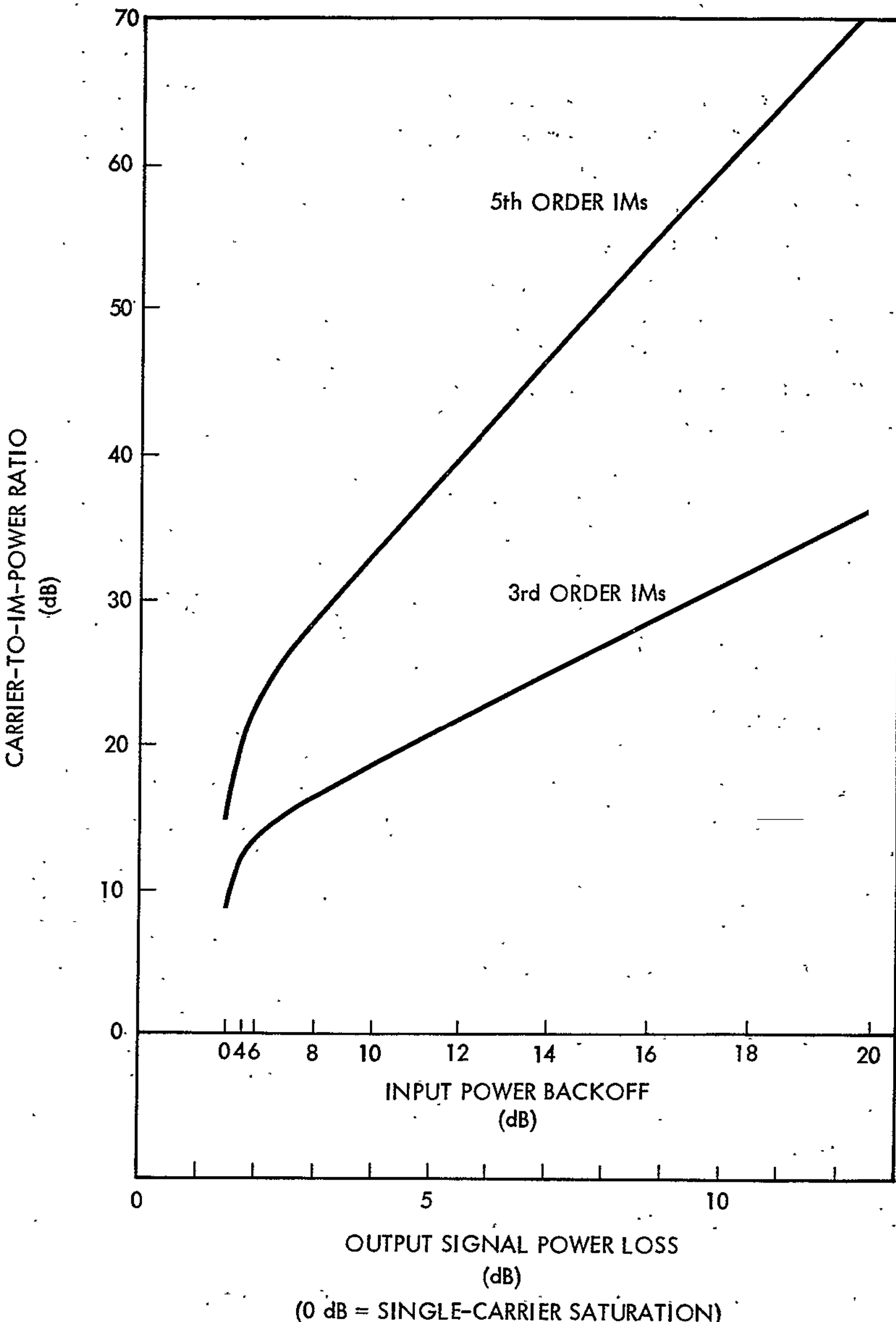


Figure 4-6: Total Carrier to Intermodulation Power in the Middle Channel for a Large Number of Equal Carriers

assignment. In the latter case, the user's request may be in response to a query from a network controller (pooling assignment) or may be self-initiated (demand assignment).

Permanent time slot assignments would normally be used only when a small number of high-duty-cycle users are to be accommodated. When a large number of infrequent users are to be serviced (as in the MMACS system), temporary time-slot assignments are called for.

Slot assignment by polling implies a fixed (and moderate) number of users each of which is normally expected to be active. In a system such as that envisioned by the Statement of Work, the total number of users would likely be large while the number of users active at any time might be small. Therefore, a demand assignment approach appears to be appropriate. Subsets of high-duty-cycle users can also be accommodated by permanent time slot assignments.

4.2.1 Frame Design and Capacity

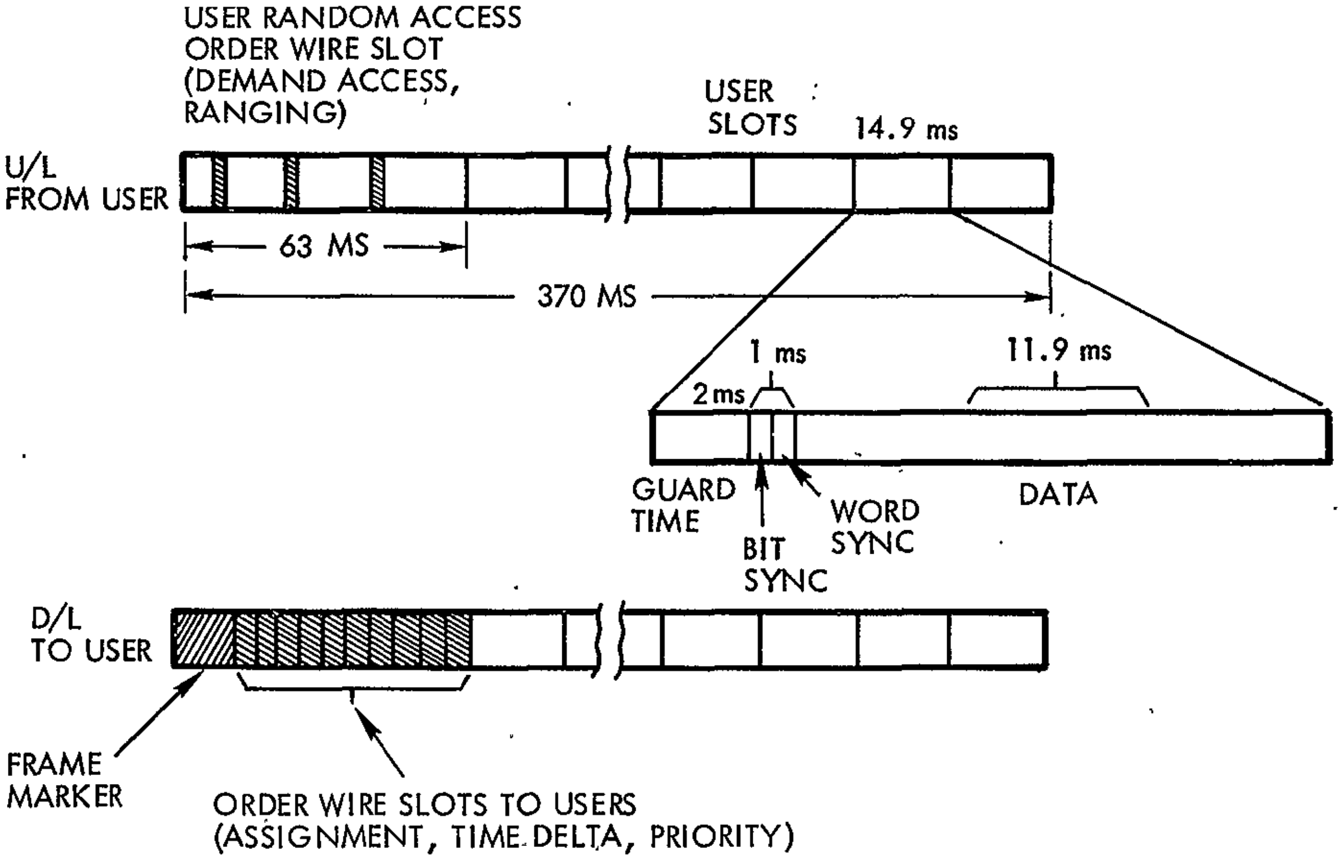
A typical design example for a TDMA frame format is shown in Figure 4-7. This frame accommodates 20 users at R_d = 16 kbps source data rate (CVSDM for voice). The burst rate is R_b = 500 kbps. Each of the 20 users is assigned to a 14.9 ms user slot within a frame of length L_f = 370 ms. The user slot consists of a 2 ms guard time to allow for timing instability, a 1 ms data synchronization preamble and a data slot of length T_d = 11.85 ms. The data rate is

$$\frac{T_d \times R_b}{T_f} = R_d$$

or

$$\frac{11.85 \times 500 \text{ kbps}}{0.37} = 16 \text{ kbps}$$

as required. The first slot in both uplink and downlink is a 63 ms order-wire slot used for demand access and control.



BURST RATE	500 kbps
FRAME TIME	370 ms
USERS PER FRAME AT 16 kbps PER USER	20

Figure 4-7. TDMA Frame Format

Acquisition of a user slot requires the receiver to synchronize to a squarewave bit synchronization pattern and a fixed word synchronization preamble. Noncoherent modulation is used so that carrier phase acquisition is not required. Bit synchronization is accomplished by a digital transition tracking loop with dual bandwidth for acquisition and tracking. The DTTL can acquire very rapidly. For example, in less than 1 ms it can acquire burst data at 19.2. kbps with E_b/N_0 greater than 7 dB (Reference 15). At the higher 500 kbps burst rate at the same E_b/N_0, acquisition would occur in about 40 s. This would require about 20 preamble bits. Word synchronization is accomplished by a fixed preample which is detected by correlation with a local code sequence. The preamble is identical for all users to simplify production of the terminals. The frame design allows 0.5 ms for bit synchronization and 0.5 ms for word synchronization. Transmitter-receiver RF switching and clock instabilities require a 2 ms guard time (Reference 15).

4.2.2 Demand Access

The assignment of time slots within frames is controlled by the system control station. When a user wishes to enter the system the user observes the downlink frame marker (a coded sequence of bits at the first of each downlink frame). This determines gross system timing, i.e., the user is now synchronized to within his range uncertainty. The range uncertainty within CONUS is a maximum of 10 ms. The user transmits a demand request in the uplink order-wire slot. Since this is 63 ms long the user positions his transmission near the center with a maximum of 10 ms error and, therefore, the order-wire message does not interfere with communication slots.

The system control station upon receipt of a request compares the implied user timing with the standard system timing. The timing delta is encoded and transmitted to the user, which readjusts its clock to be synchronized with system time. User frequency stability of ± 1 pp 10^9 per second

and ± 1 pp 10^7 per hour with a non-ovenized crystal can be obtained.* This means that the user terminal can track system time after one hour to better than 0.36 ms absolute error which is small relative to the guardtime of 2 ms. If desired, the terminal can update its system timing on request from the net control station by simply transmitting another ranging burst in the order-wire slot.

The system control station informs the user via the downlink order-wire of the outcome of the access request. Each order-wire message contains all the information relevant to a link connection, i.e., transmitter and receiver ID, full-duplex or half-duplex, voice or data, priority, user slot or slots, and so on. This requires less than about 100 bits or less than 0.2 ms at the 500 kbps burst data rate. The order-wire message length, including synchronization preamble is then

$$2 \text{ ms} + 0.2\text{ms} = 2.2 \text{ ms}$$

One or more downlink order-wire messages may be contained in each 370 ms frame. The random access uplink order-wire slot is adequate to handle a conversation request rate of at least

$$\frac{1}{370 \text{ ms}} = 2.7/\text{sec} = 1300/\text{day}$$

where an 8 hour busy period constitutes a "day".

Assuming one request per conversation, this would be adequate to handle the "A" loading (see Section 3) request rate for about 260 terminals or 1040 terminals with the "B" loading per zone, since the respective request rates are 5/day/terminal and 2/day/terminal.

*Frequency Electronics, Inc., Model FE-11 and FE-22 Non-ovenized crystal oscillators.

4.2.3 Time Delay and Buffering

The one-way time delay of the TDMA system is about 0.37 +0.3 = 0.7 sec, where 0.3 sec is the round-trip delay of the space link. Time delay for voice communication should not be made much longer than this delay since it makes conversation difficult. Thus, the frame time is limited. A longer frame could in theory accommodate more users. However, the burst rate would then increase. This is undesirable for several reasons, including complexity of the equipment and the multipath delay spreading in the mobile link. The above frame design seems to be a fair compromise between bit rate, frametime, and number of users.

A TDMA terminal would require read-in and read-out buffers for both transmitter and receiver. The buffers operate at 16 kbps and 500 kbps. The buffering requirement per terminal is

$$4 \times 0.37 \times 16{,}000 = 23{,}680 \text{ bits}$$

This would require a series of shift registers.

4.2.4 TDMA Features

A feature of TDMA is its switching and routing flexibility. One example occurs in inter-zone communication for a time-zone coverage system. The system controller maintains all four frames in synchronism at the spacecraft. Hence, a user slot may easily be switched from one time-zone downlink to another by means of a 4 x 4 switch matrix (Figure 4-8). This operates somewhat as a random access commutator. Switching of the commutator occurs in synchronism with the start of each user slot. Another example of flexibility is the case of accommodating a mix of voice and lower-rate data channels. In this case, the system controller simply redefines a 14.9 ms user slot for voice as, for example three 4.95 ms user

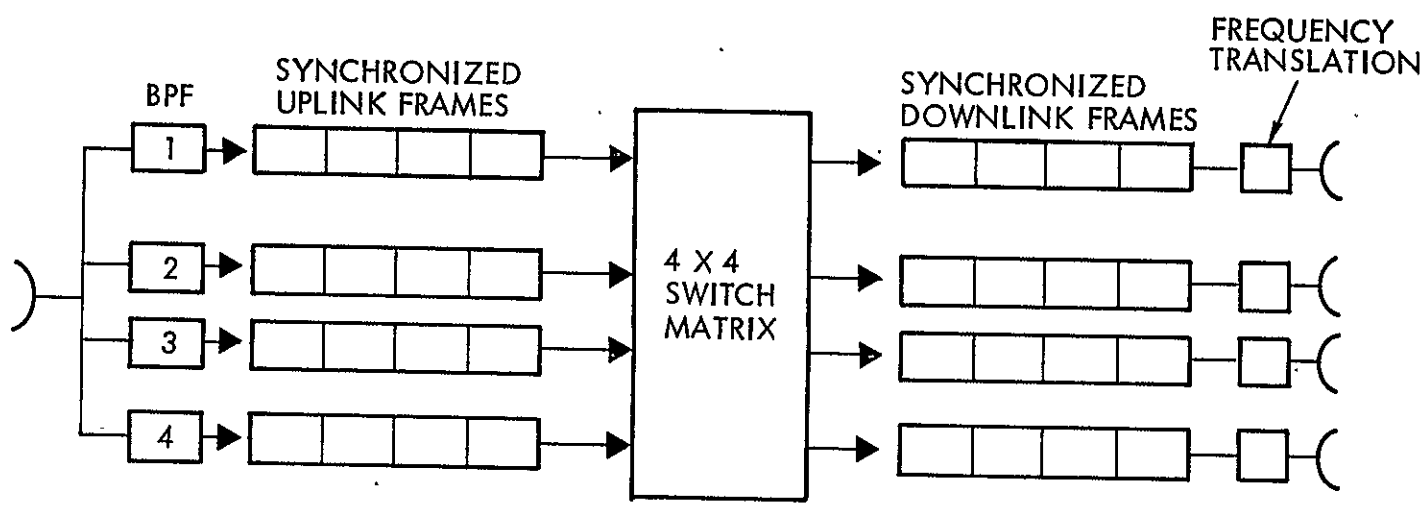


Figure 4-8. TDMA Interzone Switching

slots for data. Since the 3 ms overhead per slot is a constant, the data occupies only 1.95 ms. The data rate is

$$\frac{1.95}{370} \text{ 500 kbps} = 2{,}635 \text{ bps}$$

Thus, the 2,400 bps data could be accommodated in the 4.95 ms slot. Because of the fixed guard time, the TDMA system becomes more inefficient for the lower rate data (75 and 300 bps). A maximum of four slots can be squeezed into one voice slot since 5 x 3 ms > 14.9 ms.

The capacity of a TDMA scheme depends on the maximum burst data rate which in turn is a function of the carrier to noise density. Capacity can be increased by using a hybrid TDMA/FDMA scheme. Thus, several 500 kbps TDMA systems can be accommodated in a few MHz of RF bandwidth. In the time-zone coverage scheme considered in detail in Section 5, four FDMA channels are assumed. Each channel is assigned to a time zone and served by one "beam" of a multi-feed four-beam antenna. This improves the link budget by increasing antenna gain up to 6 dB. For TDMA the hybrid approach is necessary to avoid using unreasonably high burst rates. From the downlink power budget for time-zone coverage (Section 5) the available carrier to noise density is

$$\frac{C}{N_o} = 62.1 - 4.0 + 5 = 63.1 \text{ dB-Hz}$$

The voice activation factor is <u>subtracted</u> here because voice activation is not relevant for TDMA. On the other hand, because TDMA can operate saturated the 5-dB output power backoff is not required, hence, this is added back in. The net result is 63.1 dB-Hz. For the 500 kbps burst rate the S/N is

$$\frac{S}{N} = 63.1 - 10 \log 500{,}000 = 6.1 \text{ dB}$$

This is about the same S/N required by FDMA at threshold (see section 4.1.3). In other words, the downlink of the TDMA system is approximately the same as the FDMA system. However, due to overhead losses the TDMA system supports only 20 active channels per time-zone, whereas the FDMA system supports 25 (see Section 5).

4.2.5 Terminal Power

The major problem with TDMA is that in order to maintain the same uplink E_b/N_o, i.e., the same bit energy to noise density at the burst rate, the terminal power must increase in proportion to the ratio of the burst rate to the data rate. Thus, if the needed uplink RF power is about 35 watts for continuous operation, the TDMA terminal peak power would be about

$$35 \times \frac{500}{16} = 1{,}094 \text{ watts}$$

Even if it were possible to operate with no overhead losses, 20 users per frame would imply a peak power

$$35 \times 20 = 700 \text{ watts}$$

Since current technology is about 100 watts for push-pull solid state amplifiers this is a severe constraint. A processing satellite might relieve this constraint by reducing the needed E_b/N_o on the uplink (see reference 19).

4.3 CODE DIVISION MULTIPLE ACCESS (CDMA)

CDMA makes use of a set of approximately orthogonal pseudorandom noise (PN) codes so that m transmissions can simultaneously occupy the channel. Either direct sequence (DS) or frequency-hopping (FH) methods may be used as illustrated in Figure 4-9. In DS, each CDMA user spreads his own transmitted signal bandwidth to a $(\sin^2 \pi f t_c)/(\pi f t_c)^2$ type spectrum where f =

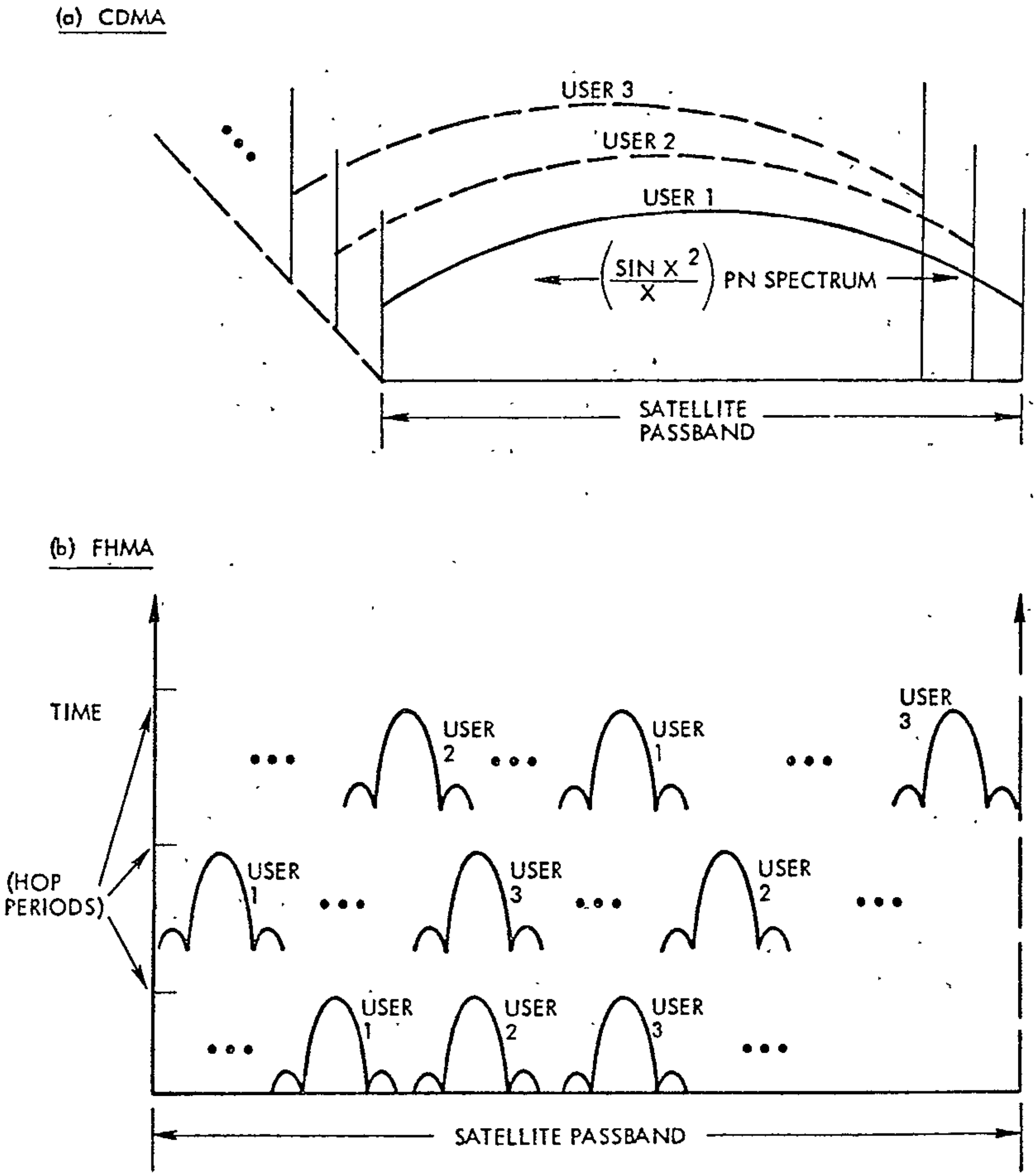


Figure 4-9. Illustration of PN Code Sequence Multiple-Access Techniques

frequency deviation from carrier and t_c = PN code chip period. In FH, each user's relatively small instantaneous bandwidth hops over the full channel under control of a PN code-generated command word.

Since each CDMA user transmits continuously over the total channel bandwidth, mutual interference degradations are caused by the increase in the noise power density produced by the m-1 other user PN code spectra in the receive channel.

Unlike FDMA and TDMA systems, which are truly orthogonal signalling sets (within the limits of filter realizations and timing errors), the CDMA signalling set is only quasi-orthogonal. CDMA signals are separated by the relative lack of mutual cross-correlation between adjacent codes. Nevertheless, for finite length codes (i.e., finite CDMA spread spectrum bandwidth) the cross-correlation is not zero. If many users occupy the same channel the m-1 cross-correlation powers add to produce a significant source of additional noise at each receiver. In order to offset the mutual noise a CDMA system requires very large BT products relative to FDMA and TDMA.

4.3.1 Capacity

A set of codes is desired which has low cross-correlation for all possible relative shifts (since code epochs are unsynchronized from different users), contains a large number of distinct codes (multiple access addresses), and finally, is not extremely long (to simplify acquisition). The first property is characteristic of antijamming spread spectrum codes. These resemble a sequence of random bits of effectively infinite length.

In this case the cross-correlation between codes is

$$C = \frac{1}{L_{AJ}}$$

where L_{AJ} is the length of the AJ code in the integration time (usually one information bit). In this case C can be made smaller by increasing the spread-spectrum bandwidth. Unfortunately, an AJ sequence would have an "address" that depends on what part of it is observed. Furthermore, its length makes unaided acquisition impractical. Thus, we turn to multiple-access codes, i.e., short-period codes which still have low cross-correlation.

The set of Gold codes (References 16 and 17a) is generated by two n-stage shift registers added modulo two producing sequences

$$\{a_i(1), \ldots, a_i(L)\}$$
$$a_i(j) = \pm 1$$

with the following properties:

$$\text{Code length } L = 2^n - 1, \; n \text{ odd}$$

$$\text{Number of distinct codes} = 2^n + 1$$

$$\text{Correlation } C = \frac{1}{L}\sum_{j=1}^{L} a_i(j)\, a_k(j+s), \; s = 1, \ldots, L$$

$$|C|^2 \leq \frac{2}{L}$$

It is seen that the cross-correlation is twice as large as a truly "random" code. However, a truly "random" code realizes its correlation only if an infinite length is examined, i.e., the "partial correlation" of a long AJ code may be several times greater than $1/L_{AJ}$.

The received signal is the sum of the m transmitted signals and random noise,

$$r(t) = \sum_{i=1}^{m} s_i(t) + n(t)$$

Here $s_i(t)$ is the signal from the i^{th} transmitter and $n(t)$ is Gaussian noise. The correlation detector at the k^{th} receiver multiplies $r(t)$ by a local code and averages over the data bandwidth. The correlator output is

$$C_k = \frac{1}{T}\int_0^T r(t) \ \tilde{s}_k(t)dt$$

where $\tilde{s}_k(t)$ is the local code (the k^{th} signal without data modulation) and T is the correlation interval (equal to the bit interval).

The signal to noise ratio of the k^{th} user may be expressed as

$$\frac{S}{N} = \left(\frac{S}{N}\right)_o \frac{1}{1 + \frac{2}{L}\sum\limits_{i \neq k}\left(\frac{S}{N}\right)_{i,o}}$$

where

$\left(\frac{S}{N}\right)_o$ = signal to thermal noise ratio of k^{th} user

$\left(\frac{S}{N}\right)_{i,o}$ = signal to thermal noise ratio of i^{th} user

$i \neq k$

If the effect of the other users is negligible, e.g., if the code length L is large or the other signal powers S_i are small or the number of users m is small, then the above expression becomes

$$\frac{S}{N} \cong \left(\frac{S}{N}\right)_o$$

as expected.

It is interesting to determine the required carrier to noise density implied by the above equation. First, let us assume equal power signals for convenience,

$$\frac{S}{N} = \left(\frac{S}{N}\right)_o \frac{1}{1 + \frac{2(m-1)}{L}\left(\frac{S}{N}\right)_o}$$

This can be restated as

$$\left(\frac{S}{N}\right)_o = \frac{S}{N} \frac{1}{1 - \frac{2(m-1)}{L} \frac{S}{N}}$$

Since the data rate is 1/T bps, the code rate is L/T bps. Assuming the CDMA channel occupancy is about twice the code rate the RF channel bandwidth is

$$B = \frac{2L}{T} \text{ Hz}$$

The carrier to noise density is

$$\frac{C}{N_o} = \frac{1}{T}\left(\frac{S}{N}\right)_o \text{ Hz}$$

where C is the carrier power, N_0 is the thermal noise density and 1/T is the information data rate. Substituting the last two equations into the expression above yields

$$\frac{C}{N_0} = \frac{1}{T}\frac{S}{N}\frac{1}{1 - \frac{4(m-1)}{BT} \times \frac{S}{N}}$$

The carrier to noise density is plotted versus bandwidth in Figure 4-10. The assumed signal to total noise ratio is

$$\frac{S}{N} = 4 \text{ dB}$$

and the assumed bit rate is

$$\frac{1}{T} = 16 \text{ kbps}$$

This corresponds to a CVSDM signal at a received BER = 5×10^{-2} with DPSK modulation. It appears from the plotted curves that a certain minimum bandwidth is required for any given number of co-channel users in the CDMA system. For example, for 28 users the minimum bandwidth required is 4.5 MHz and for 13 users the minimum bandwidth required is about 2 MHz.

If users are not all equal power, then the situation becomes worse since the effective number of "users" must be just the ratio of the sum of all the signal powers to the power of the smallest signal. The effective number of users is then much larger than the actual number of users.

Comparing the bandwidth usage of CDMA with that of TDMA we see that CDMA requires a BT product of at least

$$BT = 4.5 \times 10^6 \times \frac{1}{16,000} = 282$$

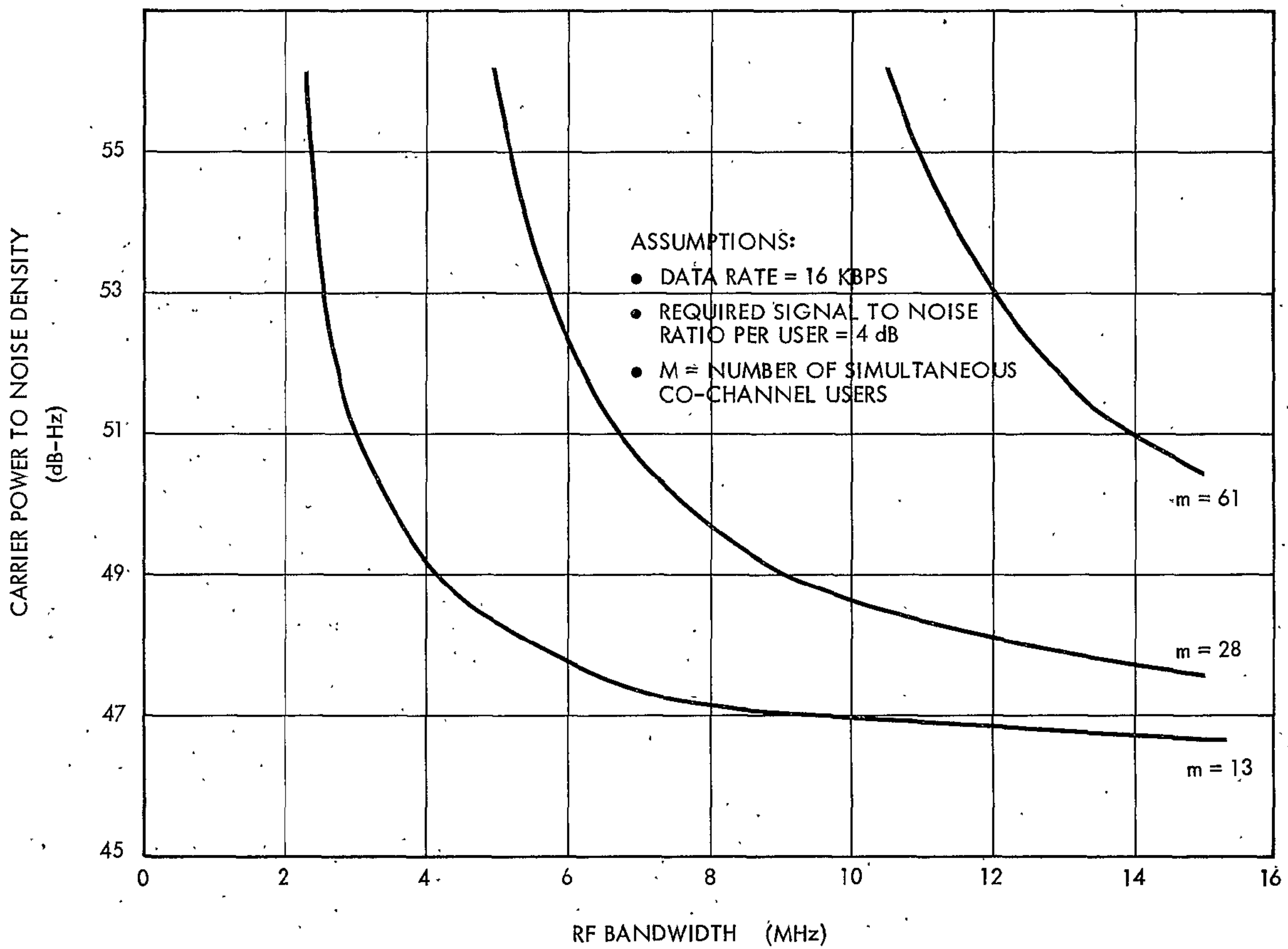


Figure 4-10. Required Carrier to Thermal Noise Density per User in a CDMA System

for 28 users. In order to prevent the signal power required from being very large, the actual BT product required is

$$BT \approx 1.5 \times 282 = 422$$

By comparison an FDMA system would require for 28 users about

$$BT = 28 \times 2 \times 16{,}000 \times \frac{1}{16{,}000} = 56$$

assuming the RF bandwidth is about twice the data rate. Thus, the CDMA system requires about 422/56 = 7 times more bandwidth than a comparable FDMA system.

This can be somewhat reduced by combining CDMA with other techniques. For example, the TDRSS multiple-access system supports up to 20 users at 26 kbps each with a multiple access RF bandwidth of 6.2 MHz. An adaptive phased-array antenna is used to form a unique beam for each user, thereby reducing mutual interference (Reference 17b).

4.3.2 Order Wire

The CDMA system requires an order-wire channel to prevent overloading and for signalling. Each user must request access via the order-wire to a system control station. The system control station limits access and enforces power control. This assures that the total cross-correlation noise is never greater than that which can be tolerated by the smallest user. The second function of the net control station is to assign and reassign codes to users and to serve as a "directory" service. Within the order-wire channel users random-access the net control station with short bursts for signalling, requests, and reports to the net control station. The same multiple-access code can be used for the order-wire and for the communication channel. When in the order-wire mode the code rate is much slower. The order-wire channel bandwidth is a fraction of the communication channel bandwidth. After receiving a request the net control station sets up the link via the return order-wire channel. The user or users involved are

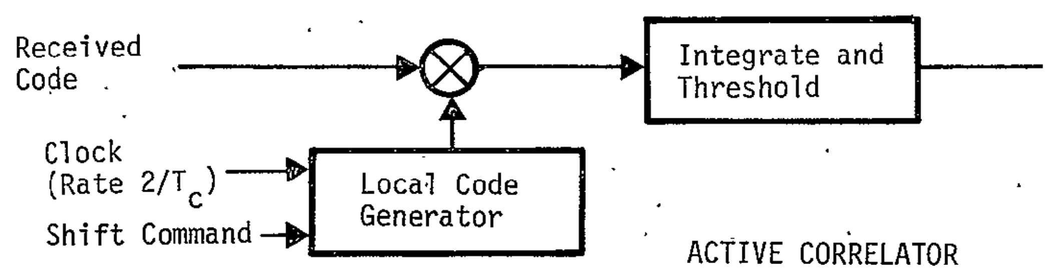
instructed to switch to the communication mode (high-rate code) and proceed with their conversation. On termination the net controller is notified that the access is over.

4.3.3 Acquisition

The acquisition time can be written as

$$\tau = 2 \times L \times D$$

where L is the code length and D is the dwell time at each 1/2 chip step. This expression applies to an active correlator, i.e., a correlator that multiplies the incoming code by a locally generated code at 1/2 chip steps until a correlation is obtained (see illustration below).



ACTIVE CORRELATOR

The dwell time is the time required to integrate over the code period,

$$D = L \times T_c$$

where T_c is the code chip time. If the RF bandwidth is

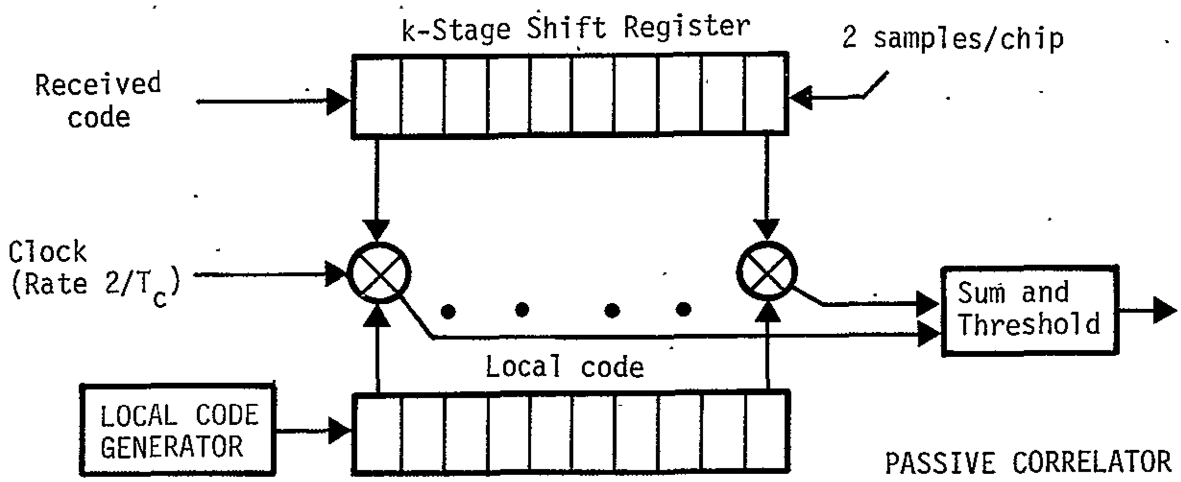
$$B = \frac{2}{T_c}$$

then we can solve for the acquisition time

$$\tau = \frac{4\,L^2}{B}$$

Because of the factor L^2 this can be fairly lengthy (10 ms or more).

A passive correlator has shorter acquisition time because it acts as a passive matched filter (see illustration). The received code is multiplied in parallel by the local code.



PASSIVE CORRELATOR

One code period is normally sufficient for acquisition, i.e.,

$$\tau = 2L\,T_c = \frac{4L}{B}$$

Normally τ is less than a millisecond.

4.3.4 Intermodulation

The CDMA system is not strongly affected by IM products. The reason for this is quite simple, namely, each IM product "looks like" another multiple-access sequence at the same frequency. Therefore, the power diverted from the original signals into IM products has the same cross-correlation noise it had in the original signals. This means the sum of the cross-correlation noise due to the reduced signals plus IMs is equal to that due to the original signals (see Reference 18).

4.3.5 Other Factors

In addition to being relatively immune to intermodulation, CDMA has several potential advantages, including

- Built-in privacy
- Built-in addressing and "dial-up" capability
- Gradual degradation with overloading
- Tolerant of frequency drift
- Immune to narrowband RFI
- Low flux density
- Saturated transponder operation.

Unfortunately, CDMA is limited in bit rate because of multipath spreading and hence its full advantages cannot be realized. Secondly, in order to support more than 20 or 30 users it appears that an RF bandwidth of 10 MHz and above is required. Many times more bandwidth is required for CDMA than for TDMA or FDMA.

4.4 SPATIAL DIVERSITY

Spatial diversity of ground terminals could be taken advantage of using multiple beam antennas on the satellite, where each narrowbeam looks at a small ground area. Unfortunately, as shown in Figure 4-11, to obtain any significant multiple access using this technique alone requires a

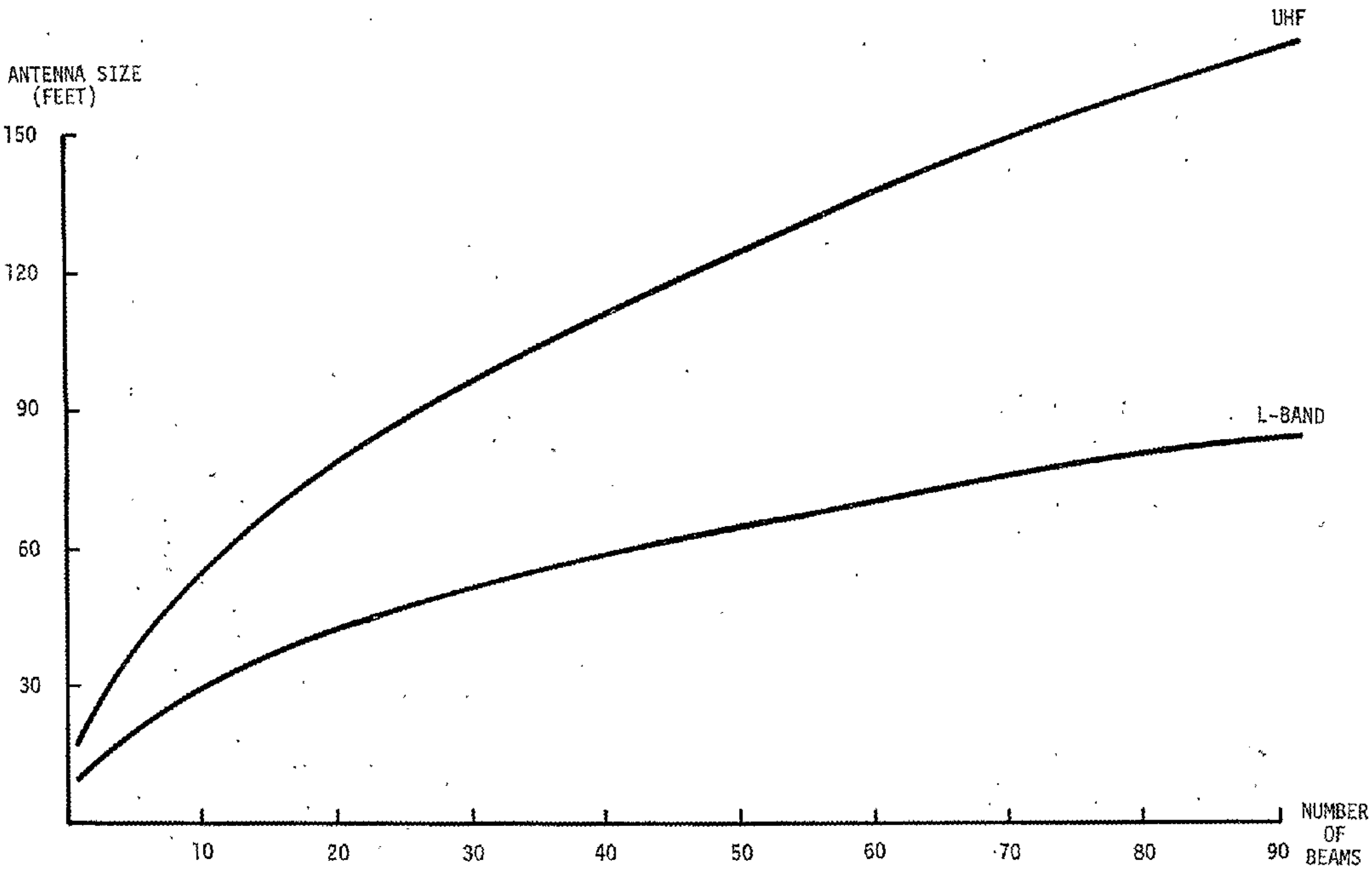


Figure 4-11. Antenna Size Versus Number of Beams Required for CONUS Coverage
(Assumes 3 dB Antenna Beamwidth)

30-foot antenna with 10 beams even at L-band. These 10 beams only allow 10 channels unless a hybrid approach is used. Therefore, SDMA should be considered only as a component of a hybrid technique to increase user capacity.

4.5 HYBRID TECHNIQUES

One variation to the CDMA approach which greatly reduces synchronization problems and receiver complexity is that of a hybrid CDMA/FDMA system. This technique partitions the channel into L subchannels, each accommodating m orthogonal PN code users. The CDMA/FDMA approach maintains the advantages of CDMA while exhibiting rapid synchronization (since PN code lengths are divided by L). Further, multiple users may be received with a common PN code in each subchannel, thereby reducing the number of distinct PN codes.

Similarly, a TDMA/FDM system exhibits advantages over a pure TDMA system (e.g., lower peak power, lower burst rates) as already discussed.

Another possibility is a hybrid X/FDMA/SDMA system where X can be either FDMA, TDMA, or CDMA. Thus, the coverage area (CONUS) is divided into zones by a multibeam antenna (SDMA) realizing increased antenna gain and dividing the total number of users into manageable groups. The use of FDMA between zones provides further isolation. Within each zone the MA technique (FDMA, CDMA, or TDMA) is selected on its merit as outlined below.

4.6 MULTIPLE ACCESS TRADEOFFS FOR COMMUNICATION

Although CDMA has many advantages it requires about 7 times more RF bandwidth than TDMA or FDMA (see Section 4.3). In addition, its terminals would be the most complex of the three types. Given the difficulties associated with CDMA, there remains only the option of using TDMA or FDMA for transmission of voice, FAX, and data. Further possibilities include using different schemes for the uplink and the downlink if a full processing satellite is assumed (similar to that proposed in Reference 19).

Advantages of FDMA are its simplicity and its efficient use of the available bandwidth. Disadvantages of FDMA are its susceptibility to intermodulation products, to narrowband interference, and a lack of privacy.

The attributes of TDMA are almost the opposite of FDMA. Its advantages are in its relative freedom from intermodulation products, from narrowband interference and the degree of privacy it provides. Its disadvantages are its complexity, relatively inefficient use of available bandwidth, and its requirement for ground terminals with ranging and synchronization and high-power amplifiers.

First, the TDMA system is considered. According to the example system design already discussed the TDMA capacity is slightly less than a comparable FDMA system, due to the overhead time allotments. The terminal complexity is another disadvantage.

The major factor here is the high power output required. For the slot times discussed (>10 ms) a power amplifier (solid state) is operating essentially CW and presently foreseeable RF outputs are 40 60 watts. Since 600 ~ 700 watts are required in theory for a 20-slot frame system this factor alone would appear to rule out TDMA. A high EIRP ground station (i.e., large ground station antenna) would seem to be required for TDMA.

An advantage of FDMA is that voice activation of the ground transmitter can be effectively used. That is, for voice transmissions, if the signal level is below some threshold, nothing is transmitted. This means that the available satellite transmitter power can be assigned to only those bands currently active. Since a conservative estimate is that only 40 percent of the channels are active and some estimates are as low as 25 percent (Reference 20), a boost in downlink power of between 4 and 6 dB can be expected merely by using automatic gain control on the satellite downlink power. TDMA cannot conveniently take advantage of voice activation because the transmitter is already assumed to operate saturated.

In order to reduce (but not eliminate) the effects of a nuisance jammer in FDMA, it is possible to select a channel in which the measured received signal energy before assignment is a minimum. This would require filters for each channel and monitoring at a ground station.

Maintaining a high degree of privacy using the FDMA system will be difficult. In the current design we assume the capability to flexibly and inexpensively serve a large number of users is more critical than privacy. Some steps can be taken to increase privacy. For example, the terminals within the system can be designed so that they cannot be tuned to unauthorized channels. Analog privacy encoding techniques (analog "scramblers") such as frequency inversion, masking, or band-splitting can be used against unsophisticated and casual eavesdroppers.

An additional advantage of FDMA is that it does not require digital voice. Not only is digital voice slightly more complex in terminal implementation, there is regulatory opposition to its usage for mobile services (Reference 21). Furthermore, the RF bandwidth and power required for digital voice is slightly more than narrowband FM, as already discussed. [However, a new technique for separately encoding different voice frequency bands may reduce the required digital voice data rate to less than 10 kbps (Reference 22a)].

The FDMA system is potentially capable of multiple access efficiency at least as high, or higher than a digital system (CDMA, TDMA). This assumes the system is provided with order-wire signalling so that demand access and rapid reassignment of channels is possible. Since all TDMA schemes possess such network control it sometimes seems that TDMA per se is more efficient than FDMA, which is not true. Furthermore, it is <u>not</u> necessary in the FDMA system for all terminals to use the demand-access scheme, or be under the control of a system control station. Some simple terminals may use fixed frequency assignments. In the TDMA system, <u>all</u> terminals must be fully controlled, i.e., a TDMA system can<u>not</u> start simply and add sophisticated terminals with growth as a FDMA system can.

Thus, an FDMA system with spatial diversity is assumed as the baseline. A detailed system description for the current application is contained in Section 5.

4.7 MULTIPLE ACCESS FOR CHANNEL REQUEST AND ASSIGNMENT

Because the MMACS system is intended to provide access to a large number of users--eventually tens of thousands--and bandwidth and power limit the number of channels to approximately 100, it is necessary to proide an effective channel request and assignment mechanism. At the same time, the user terminal cost must be kept low and the user interface simple.

Because of the large time delays required for a signal to travel up to the satellite and back to the earth (approximately a quarter of a second), monitoring of the various channels by the potential transmitter and selection of a free channel is likely to result in frequent conflicts. For example, if we assume 10,000 users, an average conversation lasting 30 seconds, and 10 conversations by each user each day, we find that, on the average, 35 channels are being used at all times. Since conversations are 30 seconds long, 35 requests must be made every 30 seconds.

Even if we assume that the number of conflicts resulting from merely seizing a free channel is acceptable, it is still necessary to notify the receiver that he should be listening. This would require continuous monitoring by every terminal of all potential channels.

A more practical scheme would be one in which a central authority receives requests and notifies the transmitter which channel to use and the receiver which channel to listen to. This system can easily be extended to allow the central authority to terminate low priority users when all channels are busy and replace them by high priority users.

In this case the central authority would either be a ground computer reached via the satellite or a processor on board the satellite. Having the processor on board the satellite would save approximately a quarter of

a second due to elimination of a satellite to ground round trip and would avoid the need for an additional uplink and downlink.

Gaining access to the central control is once again a multiple access problem. In this case, however, the data rate is much lower than in the primary data channels, and the duration of a message is much shorter. Furthermore, an occasional conflict in requesting channel access only means a slight delay (several seconds) before gaining access to a channel and is therefore tolerable.

Table 4-1 shows the parameters that must be passed to the central control to allow it to perform a channel allocation and notify the receiver and transmitter. Thus, a total of 40 bits are required. In order to prevent ambiguity in the case of conflicting simultaneous requests, several extra bits should be added as error protection. In addition, a preamble is required to allow the satellite's receiver to synchronize on the message. The satellite either forwards this message to the ground or processes it on board. The processing is the same in either case.

The central station control logic is shown in Figure 4-12. The information is checked for consistency. Then, if the message is a request for a start up of transmission, an available channel is located. If no channel is free, the priority of the request is compared with the priority of the current users. If the request priority is higher than that of one of the current users, a message is sent down to that current user terminating his access, and notifying the new receiver and transmitter.

All terminals must continually monitor the downlink control channel to respond to notification from the satellite. The downlink control channel must convey the information shown in Table 4-2. This requires 43 bits. Again, a preamble is required to allow the terminal to synchronize on the message.

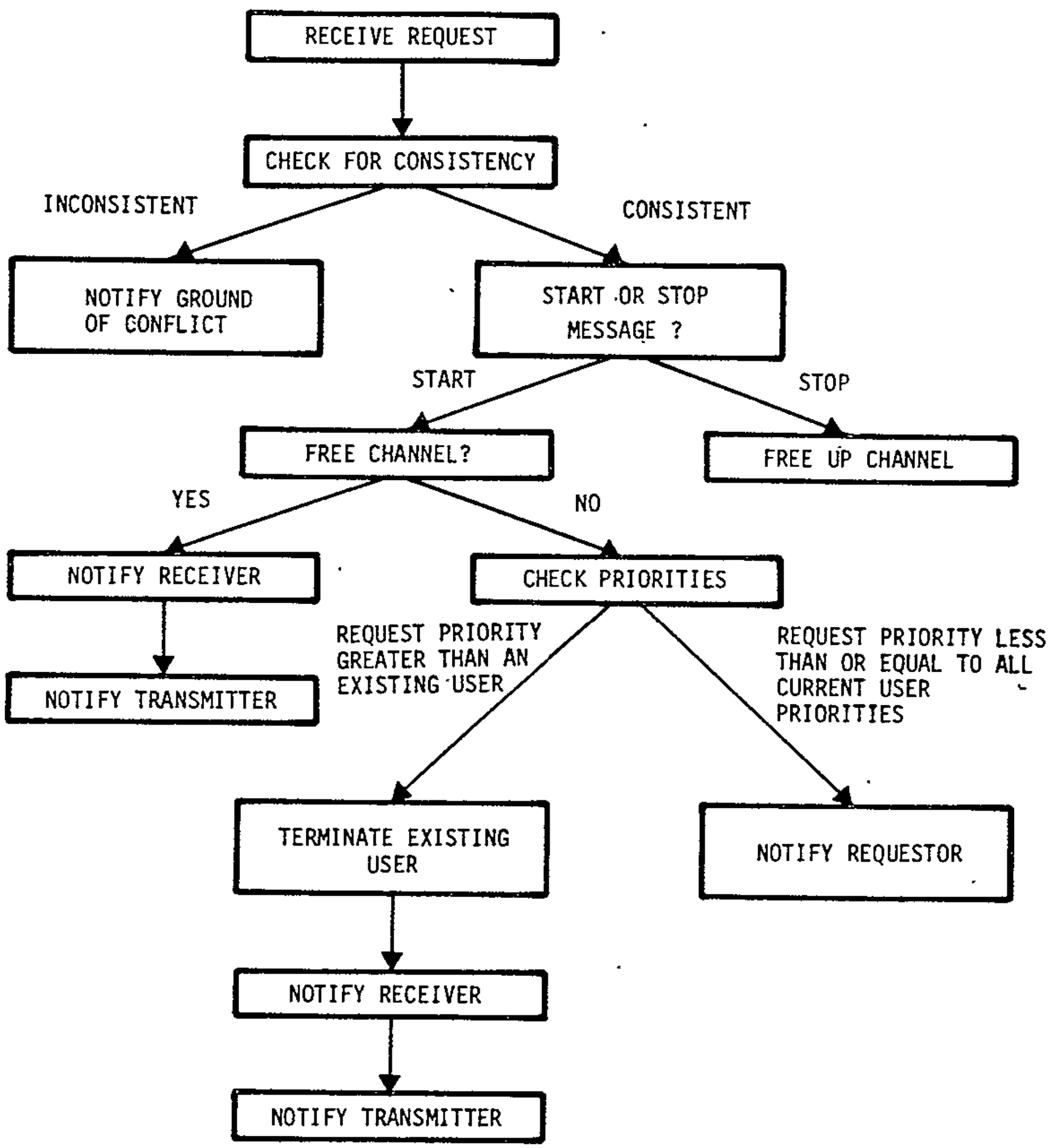


Figure 4-12. Demand Assignment Logic

Table 4-1. Demand Request Information

Information	Number of Bits
Transmitter ID	17
Receiver ID	17
PRIORITY	2
DATA TYPE*	3
START/STOP NOTIFICATION	1

*Voice full duplex, voice half-duplex, high rate fax, low rate fax, high rate data, low rate data.

Table 4-2. Satellite Control Information

Information	Number of Bits
Transmitter ID	17
Receiver ID	17
Channel	7
Start/Stop	1
Transmit/Receive	1

Now the minimum time between a request and a response is a quarter of a second due to the round trip time from earth to satellite. Assuming that a rate of 2,400 bps is employed for the demand access data (consistent with the communication data rate), a request and notification of transmitter and receiver occurs in half a second. Therefore, we assume minimum uplink and downlink control channels bandwidths of 5 kHz.

Assume that the duration of one message on the order-wire uplink is x seconds and that the average time between requests is r. Then assuming a Poisson distribution of request times we have the probability of a conflict between requests is

$$P_c = 1 - e^{-x/r}$$

during each request. For example, if x is 1/24 of a second (100 data bits at 2,400 bps) and r is 0.4 second, then $P_c = 0.1$. This means that every tenth request by a particular user will have to be repeated. This can be reduced by assigning two or more 5 kHz data channels to the order-wire since 5 data channels occupy a single voice channel. Two order-wire channels would support 2/.4 = 5 requests/second.

The complexity required of the order-wire is very dependent on the uplink transmission rate and the rate at which requests are made. Since it is impractical to give every user his own frequency, code, or time slot, even on the order-wire, some conflict or probability of conflict is inevitable. The capacity of the uplink order-wire can be increased by improving the method of retransmission when a conflict occurs. Such schemes have been considered for the ALOHA random access data network. This network originated for remote computer terminals and uses random access to a common channel to obtain an average capacity of about 37% of saturation (see Reference 22b).

5. FDMA SYSTEM DESIGN (SELECTED TECHNIQUE)

5.1 SYSTEM DESIGN SUMMARY

The FDMA system operates with 100 channels total (voice channel equivalents) in CONUS. The voice channel spacing is 25 kHz with narrowband FM voice modulation. Data channel spacing is 5 kHz with FSK modulation utilizing the same demodulator as the voice channel.

The spacecraft transponder operates as a "bent-pipe" repeater with the addition of various cross-strapping options for interzone and full CONUS downlink coverage. A multibeam antenna provides communication to individual zones with a time-zone coverage being the baseline.

Each zone includes order-wire channels for demand access and control. Order-wire messages are sent at 2400 bps utilizing the data terminal modulator/demodulator. Each terminal is assigned an address and may request a channel from the system controller. The system controller assigns channels from a "pool" of demand-access frequencies and notifies the transmitter and receiver(s). Frequency selection at the terminal is automatic.

The system accommodates a mix of terminals from those (with no demand access capability) assigned permanently to a frequency under a base station control up to a full demand access terminal. The terminals are single-channel and either mobile or portable. The mobile terminal utilizes a conical coverage antenna (e.g., a narrowband conical spiral) which does not require pointing.

The baseline frequency is UHF (820 to 870 MHz) for both uplink and downlink. Another possible scenario suggested in discussions with NASA is UHF mobile and a Ku-band (12/14 GHz) base station wherein mobiles communicate only with a base station. This effectively reduces the UHF power required since the spacecraft Ku-band downlink carries roughly half the channels.

The MMACS can utilize either CONUS coverage, a 4-zone coverage or multizone (8-zone for example) coverage. The obvious advantage of the narrower coverage is the reduction of the power required for the rf amplifier which is probably the key spacecraft technology area. The antenna aperture is of course increased and the communications ground and spacecraft equipment becomes more complex because of the requirement for interzone channels and switching.

A significant advantage of the reduction of UHF power is the reduction of the multipaction problem. In addition, greater channel capacity is possible with zonal coverage.

Intermodulation products (IMP's) due to nonlinear effects in passive devices such as switches, circulators, antennas, etc., are a potential problem area since the gain of the spacecraft transponder must be high (with a weak uplink and a strong downlink). Zonal coverage alleviates this problem because of the improved receive antenna gain and lower required rf amplifier power output.

5.2 MULTIPLE ZONE COVERAGE CAPACITY AND FREQUENCY PLANNING

The multiple zone coverage implementations to be discussed include a time zone or four zone coverage and an eight zone coverage. For time zone implementation, CONUS is divided into four overlapping zones as shown in Figure 5-1. As can be seen, good coverage is achieved with a zone area of 3.2° by 2.4°. The spacecraft is stationed at 100 degrees west longitude. The antenna gain is estimated to be 32.6 dB at edge of coverage utilizing an aperture of approximately 9.8 x 7.6 meters with an eight-feed cluster, two per region.

An attractive feature of a multiple zone coverage is that the satellite rf output power is reduced and is divided among a number of feeds. This considerably simplifies the linear amplifier design and lessens the chances of a multipaction problem. The design chosen uses a single 16-watt solid state device for each antenna feed. This rf power level is about the upper limit for a UHF linear amplifier using a single existing device.

The downlink rf power budget is shown in Table 5-1. The system capacity is 25 equivalent voice channels per zone, i.e., 100 voice channels for CONUS. Other than the spacecraft antenna gain and rf power output, the following groundrules are noteworthy:

1) The ground user G/T is -24 dB/°K. This is calculated from a total system noise temperature of 500°K and a conservative antenna gain of 3 dB.

2) The uplink contribution to the downlink assumes an uplink of 56.6 dB-Hz (Reference 2).

3) The margin consists of 8 dB fading and 1 dB additional margin.

4) The duty cycle assumes that only 40 percent of the users will be speaking simultaneously at any time.

Table 5-1. Time Zone Coverage - Downlink

Antenna Gain (E.O.C.)		32.6 dB
rf Power/Feed (16 W)		
rf Power/Zone (32 W)		15.1 dBW
Output and Pointing		-1.0 dB
	EIRP	46.7 dBW
Path Loss		183.6 dB
Ground Station G/T		-24 dB/°K
Boltzmann's Constant		228.6 dBW/Hz/°K
Received C/N_0		67.7 dB-Hz
Uplink		-0.6 dB
Margin		-9.0 dB
Duty cycle (40%)		4.0 dB
C/N_0 Available		62.1 dB-Hz
C/N_0 Required/Voice Channel		48 dB-Hz
Number of channels		14.1 dB = 25/Zone

5) The C/N_0 required (voice channel) is assumed to be 48 dB-Hz. This is adequate for narrowband FM.

Of the 25 equivalent voice channels available per zone, most would be dedicated to intrazone service while the remaining channels could be reserved to interzone service. There are a number of options for this arrangement depending on the nature of the mobile traffic (i.e., mostly local or mostly between points throughout CONUS). One method is to designate a number of channels as CONUS channels. These are accessible throughout CONUS on both transmit and receive. For example, four CONUS channels could be allotted together with 24 intrazone channels in each time zone for a total of 100 channels.

5.3 FREQUENCY PLANNING FOR CONUS COVERAGE

Figure 5-1 shows a frequency plan without frequency reuse which occupies 2.5 MHz for the total of one hundred 25 kHz channels. This spectrum occupancy is probably not unreasonable for the MMACS application. However, a higher capacity system with many more channels would most probably demand spectrum conservation and frequency reuse.

5.4 EIGHT ZONE COVERAGE

An example of a higher capacity system with frequency reuse is shown in Figure 5-2. The 8-zone coverage shown is achieved with a 2.2° x 1.8° zone providing a 35.5 dB edge of coverage gain. The antenna aperture is 13.7 x 11 meters. Using 16 watts for each of 16 feeds, the rf power budget in Table 5-2 shows a total capacity of 8 x 50 = 400 channels.

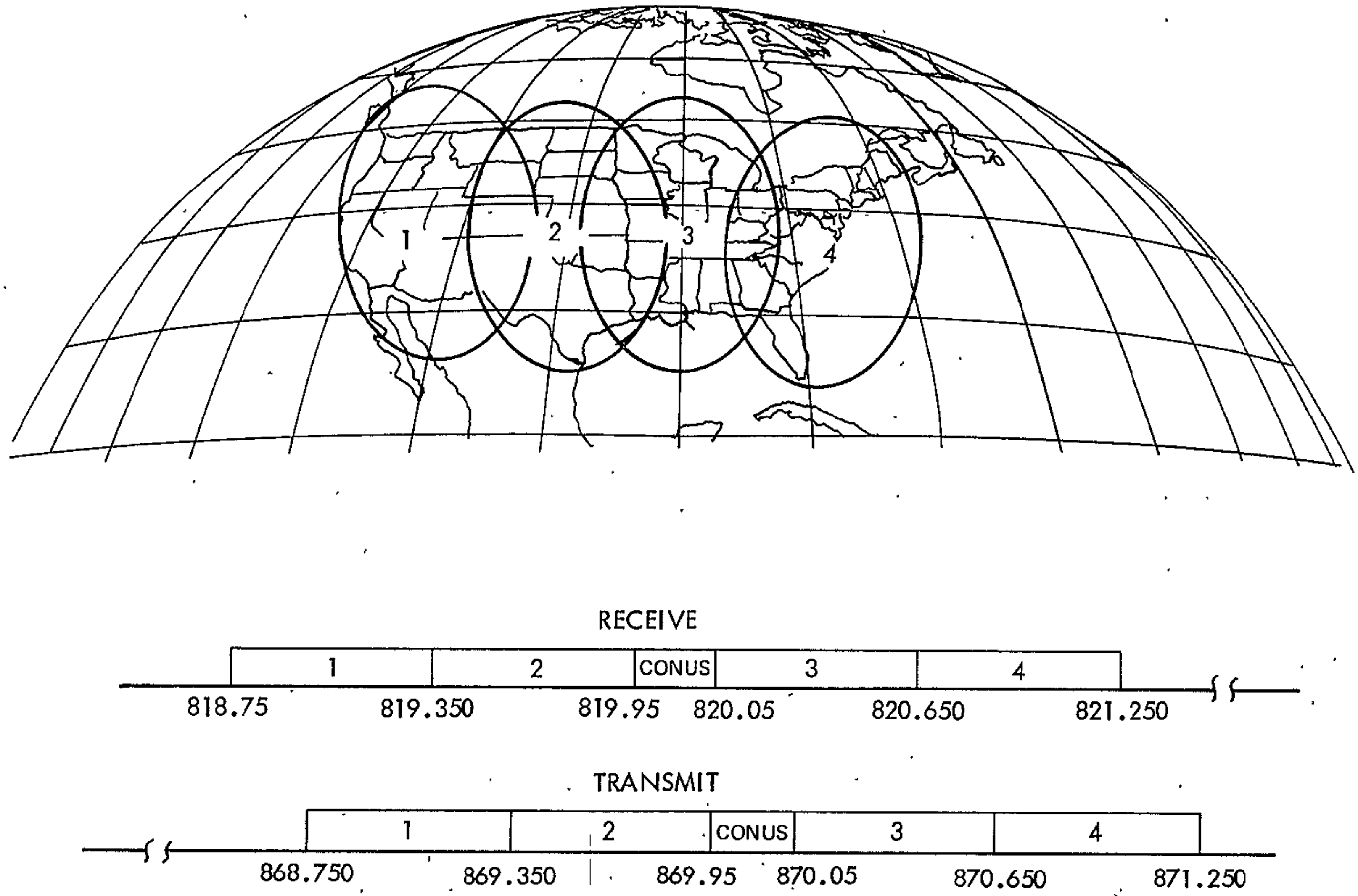


Figure 5-1. Time Zone Coverage and Frequency Plan

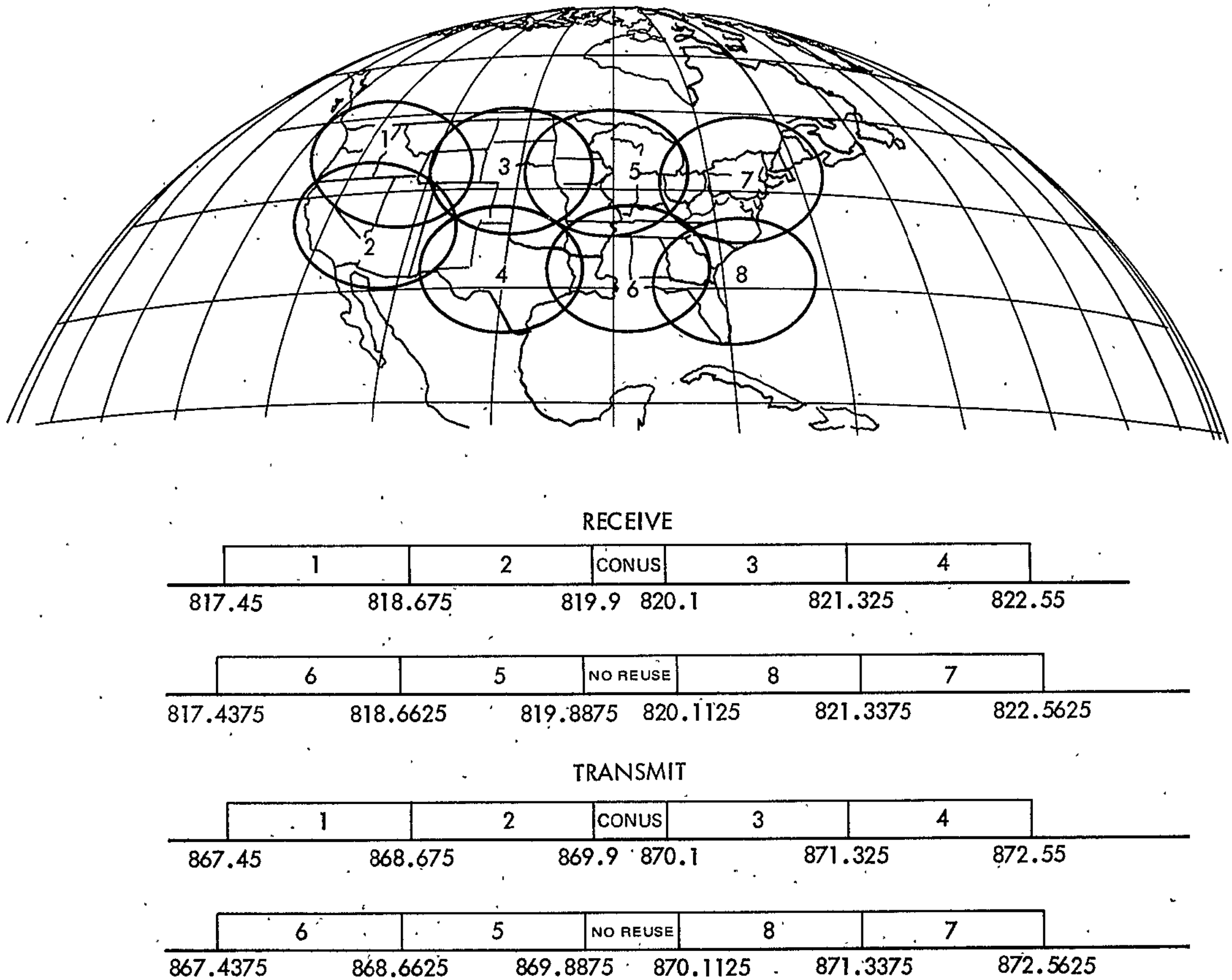


Figure 5-2. Eight Zone Coverage and Frequency Plan

Table 5-2. Eight Zone Coverage - Downlink

Antenna Gain (E.O.C.)		35.5 dB
rf Power/Feed (16 W)		
rf Power/Zone (32 W)		15.1 dBW
Output and Pointing		-1.0 dB
	EIRP	49.6 dBW
Path Loss		183.6 dB
Ground Station G/T		-24 dB/°K
Boltzmann's Constant		228.6 dBW/Hz/°K
Received C/N_0		70.6 dB-Hz
Uplink		-0.6 dB
Margin		-9.0 dB
Duty cycle (40%)		4.0 dB
C/N_0 Available		65.0 dB-Hz
C/N_0 Required/Voice Channel		48 dB-Hz
Number of voice channels		17 dB = 50/Zone

Frequency reuse is feasible in this case because of the increased spatial isolation. Using an e^{-x^2} or Gaussian model for the main antenna lobe, a relative attenuation of roughly 11 dB is calculated between Zone 1 and Zone 6 signals. This assumes an angular separation of 2.4 degrees from the center of Zone 1 to the 3 dB edge of Zone 6. Adding this to the 10 to 14 dB of isolation from frequency staggering provides a total of 21 to 25 dB isolation without recourse to polarization isolation.* Frequency reuse restricts the spectrum occupancy to roughly 5 MHz (actually 5.1 MHz since the eight CONUS channel frequencies are not reused) for 400 channels instead of 10 MHz without reuse.

*Note that in order to provide maximum spatial separation between bands zones 1 and 6, 2 and 5, 3 and 8 and 4 and 7 use the same frequency bands. In addition, the reused bands are staggered by 12.5 KHz in order to obtain additional isolation. This serves to line up the edges of 25 KHz channels in one zone with the centers of corresponding channels in the other zone.

5.5 SPACECRAFT IMPLEMENTATION

A simplified, functional block diagram of the payload transponder is shown in Figure 5-3. No attempt has been made to show hardware implementation, gain distribution, redundancy, etc. Single conversion frequency translation is shown. Similar applications such as FLTSATCOM* and the AEROSAT** proposed designs utilized dual conversion with channel separation at intermediate frequencies in the neighborhood of 35 MHz. The proposed design uses surface acoustic wave device (SAWD) filters for channel dropping. An unloaded Q of better than 10,000 is required for the CONUS channels which could have a bandwidth as low as 100 kHz. These devices are in advanced development and have had little, if any flight experience. Should this prove unfeasible, then the more conventional IF crystal filters can be used with somewhat increased transponder complexity.

The rest of the transponder is a straightforward state-of-the-art except for the output power amplifier. To date, most solid state amplifiers built for spacecraft use have been single carrier operated near saturation. The PSCS application is a linear, multiple carrier device. The advantage of the zone coverage rather than total CONUS coverage is especially apparent here. For CONUS coverage, an amplifier with a 300 watt output has been suggested. A solid state implementation concept of the 300 watt amplifier using existing 40 to 60 watt rated devices backed-off to operate Class A at about 16 watts requires at least 24 transistors plus 6 drivers.

By contrast the proposed scheme uses an amplifier with one or at most two power transistors per amplifier. Amplifier design can be derived from a multi-carrier amplifier developed by TRW for FLTSATCOM at 250 MHz. In that case, a 32 watt output is achieved using two final stage transistors

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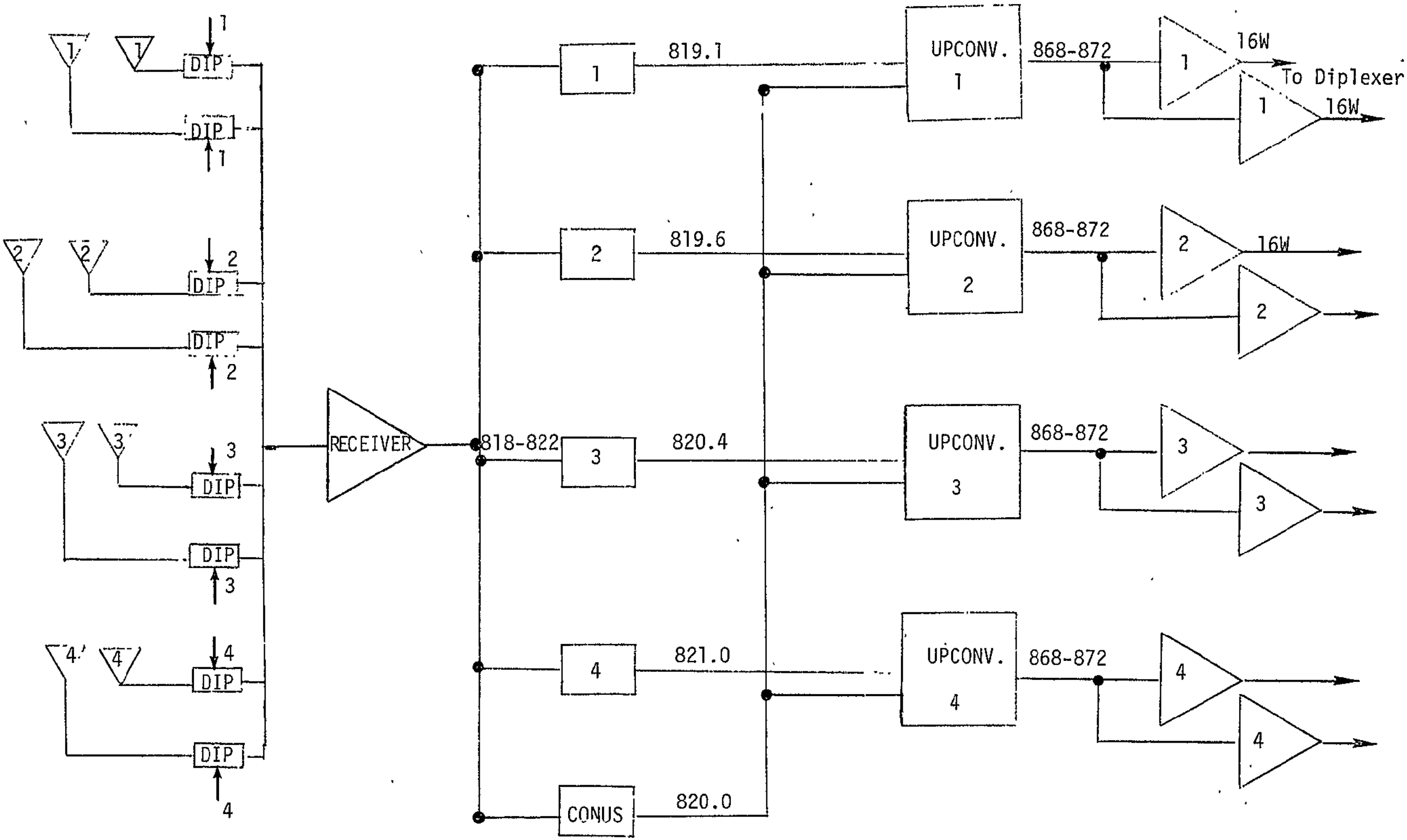
* M.J. Friedenthal & E.K. Heist, "Fleet Satellite Communications Spacecraft," WESCON, Los Angeles, Ca. Sept. '76.

** "Proposal for Aerosat Spacecraft", TRW Proposal No. 22280.000, Submitted to Aerosat Space Segment Programm Office, June 15, 1976.



NOTE: Redundancy Not Shown

Figure 5-3. Time Zone Coverage Transponder

each putting out 17 watts at 38 percent efficiency. The devices are rated at about 70 watts saturated. The overall amplifier operates at an efficiency of roughly 32 percent including driver losses and assuming a regulated input voltage of roughly 28 V ± 1 V. If power regulation is required then the dc to rf efficiency is approximately 27 percent.

Devices are available from manufacturers such as Communications Transistor Corporation, (CTC), San Carlos, California; TRW Semiconductors, Lawndale, California; and Microwave Semiconductor Corporation (MSC), Somerset, N.J. Devices in the 40 to 60 watt saturated output range at 900 MHz include the CTC-CD-2467, the TRW MRA-1417-25 and HPX-221 and the MSC-1330. A derating to 16 watts for linear operation appears to be a reasonable extrapolation from FLTSATCOM experience. An efficiency of 38 percent for the device is probably optimistic considering operation at 900 MHz instead of 250 MHz. An overall efficiency of 26 to 33 percent including driver and power conversion losses is set as a reasonable goal. The dc power required for the transponder would be in the 450 to 550 watt range. Table 5-3 lists a set of characteristics for the solid state amplifier complement for three different coverage schemes including the proposed time zone implementation.

5.6 ANTENNA

The UHF antenna requires deployment even for CONUS coverage. For the proposed time zone coverage the maximum antenna dimension is about 32 feet.

The maximum published deployed diameter is for the ATS-6 30-foot "wrap-rib" built by Lockheed.* However, this antenna was operated at frequencies up to 6 GHz, hence the surface accuracy is well above that required at the 870 MHz UHF mobile frequency. TRW is currently building the FLTSATCOM spacecraft with a 16-foot deployable antenna operating up to roughly 400 MHz. This antenna could be "extrapolated" for the present application.

*"The ATS-F and -G Data Book", Goddard Space Flight Center, Greenbelt, Maryland, Revised, Sept. 1972.

Table 5-3. RF Amplifier Characteristics

	CONUS Coverage (70 channels)	Time Zone Coverage (100 channels)	8-Zone Coverage (400 channels)
RF Power (watts)	300	128 (16 watt/device)	256 (16 watt/device)
Total Amplifier Weight (Kg)	18	7	14
Solar Array Power (watts)	1200-1500	400-500	800-1000
Solar Array (3) Weight (kilograms)	40-60	13-20	27-40
Battery Energy (watt-hr)	1440-1800	480-600	960-1200
Battery Weight (3) (kilograms)	41-60	14-20	27-40

(1) Includes all UHF amplifiers in transponder, three for two redundancy.

(2) Ten year solstice: Light weight rigid at 25 W/Kg or light weight rollup at 30 W/Kg. Weight of orientation mechanisms and booms excluded.

(3) Nickel hydrogen single battery, redundant cells. Thirty to 35 watt-hr/Kg. Charge control excluded.

The PSCS spacecraft includes Ku-band communications and TV services which require multiple spot beam and zonal coverage. Hence, the UHF and Ku-antennas could be completely independent or partially combined. For a combined approach, a dichroic subreflector has been suggested (in the PSCS May 1977 brochure) which would be reflective at Ku-band and transparent at UHF. The UHF feeds--helices, cup dipoles, or others--would be mounted above the subreflector operating in a conventional focus fed mode in any

case. The Ku feeds would operate in a cassegrain mode which enables mounting near the body. The Ku-band would utilize the body fixed central part of the reflector.

The 16-foot diameter FLTSATCOM antenna weighs about 86 pounds including support structure, feed, cable, and deployment mechanism. The TDRSS KSA 16-foot reflector is estimated to weigh 50 pounds including thermal control. Extrapolating the reflector by the area and the other items by the diameter or an appropriate percentage results in a 32 x 25 foot UHF antenna weight estimate of 100 to 115 pounds. By contrast, the ATS F,G Data Book gives a weight of 180 pounds for the 30 foot reflector without mast and feeds.

5.7 PASSIVE INTERMODULATION PRODUCTS

The UHF mobile service communications transponder may be vulnerable to the effect described by intermodulation product (IMP) interference from passive elements. As shown below, the proposed time zone implementation is the least affected. Elements such as rf switches, circulators, filters, antennas, etc., have been usually considered linear devices. However, given a weak user, i.e., a low level uplink EIRP and a high satellite EIRP, an IMP generated in the satellite transmitter chain and falling within the receiver bandpass can cause interference with the received signal. Unfortunately, for the case at hand, the remedy of a separate satellite receive antenna providing 35 to 60 dB of additional isolation would be very difficult to implement without decreasing the aperture size. This would reduce capacity or raise the price of the ground terminals. Therefore, the possible remedies remaining, should they be applicable, are frequency planning and good design practice in minimizing or eliminating the use of suspect devices.

Table 5-4 illustrates the levels of passive IMP's of concern for each of the three schemes.

A simplified block diagram of the passive intermodulation product flow is shown in Figure 5-4. The UHF amplifier is assumed to be a linear device which does not generate IMP's. The switch combiner is used to combine solid state modules and switch modules for redundancy purposes. IMP's could be generated there depending on the physical construction. The most likely place for IMP generation is in the common junction of the diplexer. Note that IMP's generated there which fall in the receiver bandpass are on the same flow path as uplink signals. Similarly, IMP's formed in the microwave connections to the antenna or in the antenna may also be on the same path as the incoming signals.

Table 5-4. Maximum IM Level Budget

	CONUS Coverage	Time Zone Coverage	8-Zone Coverage
Uplink EIRP (1)	10 to 16 dBW	10 to 16 dBW	10 to 16 dBW
Space Loss	183.6 dB	183.6 dB	183.6 dB
S/C Receive Antenna Gain	26.9 dB	32.1 dB	35.0 dB
Input Losses	1.0 dB	1.0 dB	1.0 dB
Received Signal	-147.7 to -141.7 dBW	-142.5 to -136.5 dBW	-139.6 to -133.6 dBW
C/IM Required and Margin	22 to 25 dB	22 to 25 dB	22 to 25 dB
Maximum IM Level Allowable at Antenna	-172.7 to -163.7 dBW	-167.5 to -158.5 dBW	-164.6 to -155.6 dBW
Transmitter Output per Channel (2)	6.2 to 10.2 dBW	1 to 5 dBW	-1.9 to 2.1 dBW
IM Level	-169.9 to -182.9 dBC	-159.5 to -172.5 dBC	-153.7 to -166.7 dBC

(1) Nominal to 6 dB fade uplink

(2) 40 to 100 percent of carriers present. See Tables 5-1 and 5-2.

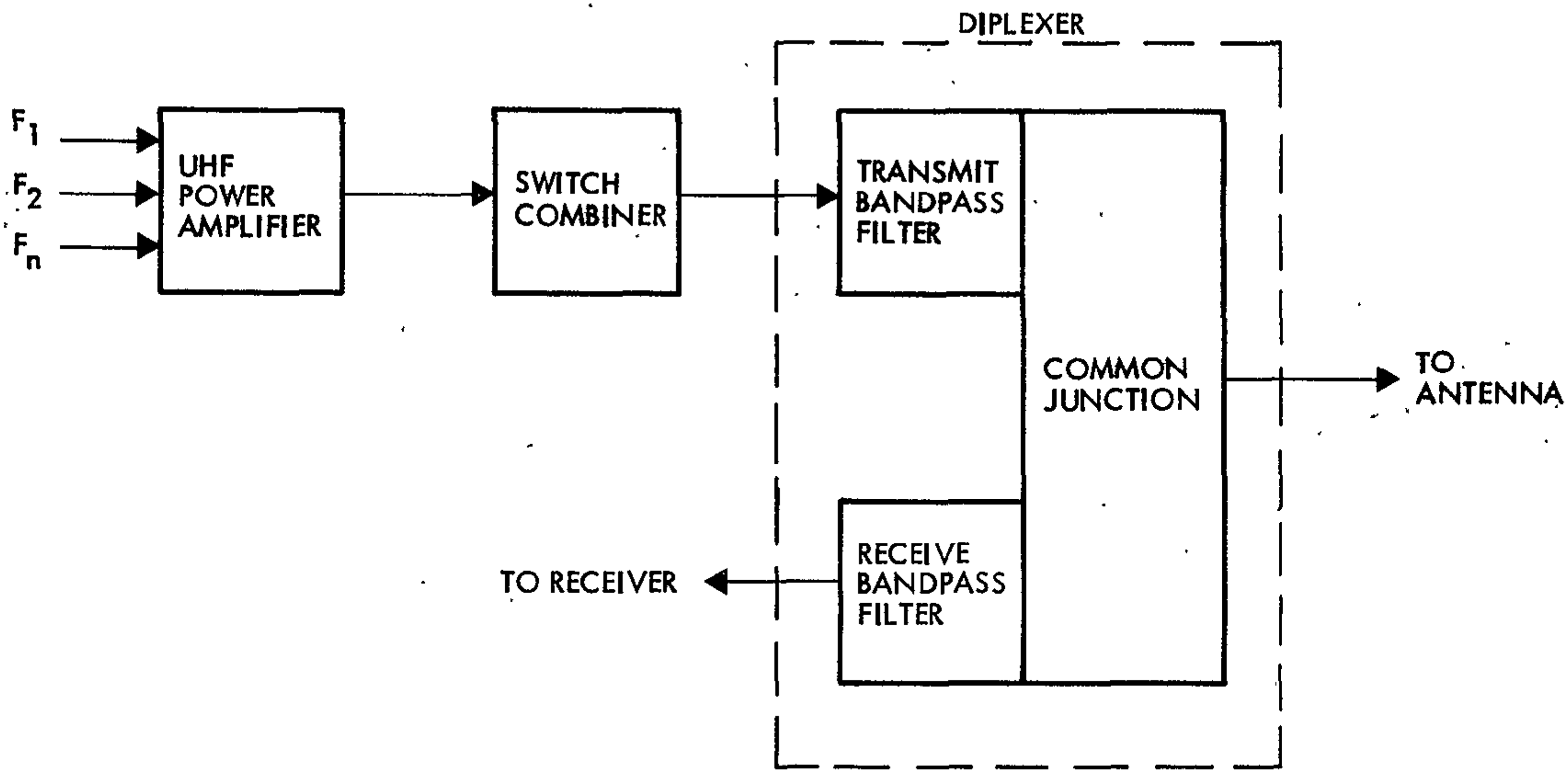


Figure 5-4. Intermodulation Product Flow

The lowest order IMP in the receiver bandpass is a function of the transmit bandwidth and the carrier spacing. Assuming an equal 25 kHz carrier spacing then the lowest order of the IMP falling in the receive band can be computed as:

$$I_{MP} = 2\omega + 1$$

where

$$\omega = \frac{f_{t_{min}} - f_{r_{max}}}{f_{t_{max}} - f_{t_{min}}}$$

and $f_{t_{min}}$ = Lowest transmit frequency in amplifier

$f_{t_{max}}$ = Highest transmit frequency in amplifier

$f_{r_{max}}$ = Highest receive frequency

For the three systems, Table 5-5 lists the lowest order IMP falling in the receive band assuming that the widest carrier spacing within any single amplifier provides the lowest IMP.

Table 5-5. Lowest Order IMP in Receive Band (Based on Diplexer Nonlinearity)

CONUS Coverage	Time Zone Coverage	8-Zone Coverage
57th order	75th order	35th order

If the IMP is created in the antenna itself, then the lowest order in the receive band will drop for the multiple beam cases since all the carriers are present. For example, for the Eight Zone Coverage frequency plan shown in Figure 5-3, IMP's are generated by carriers between 872.55 and 867.45 rather than by carriers between 870.1 and 867.45. This is shown in Table 5-6.

Table 5-6. Lowest Order IMP in Receive Band (Based on Antenna Nonlinearity)

CONUS Coverage	Time Zone Coverage	8-Zone Coverage
57th order	39th order	19th order

Figure 5-5 is a set of plots of passive IMP's made by TRW using a special FLTSATCOM facility. Note that different devices exhibit completely different behavior as to the amplitude of higher order IMP's and the way the IMP's decrease with higher order.

For example, for ferrite devices such as the circulator shown in Figure 5-5, the IMP level tends not to fall off rapidly and can even experience increase with higher order. This sort of behavior is very difficult to model. The IMP's generated by a common junction in a diplexer would generally fall off steeply as illustrated by the hybrids in Figure 5-4.

The maximum values shown in Figure 5-5 are roughly 135 dB below the carrier and the system noise level is 190 dB below the carrier. Note from Table 5-3 that we are concerned with levels 154 to 183 dB below the carrier. For Time Zone Coverage the allowable IMP level is -172.5 dBc and from Tables 5-5 and 5-6 the lowest order IMP of concern is the 39th order. Thus, the implied area of concern is the upper right quadrant in Figure 5-5 (the area above the 39th order and the -172.5 dBc level). Hence, based on two-carrier IMP's, the Time Zone Coverage frequency plan is not affected by most of the passive IMP sources. Only the circulator measurements are definitely in the region of concern. Unfortunately, with the wide

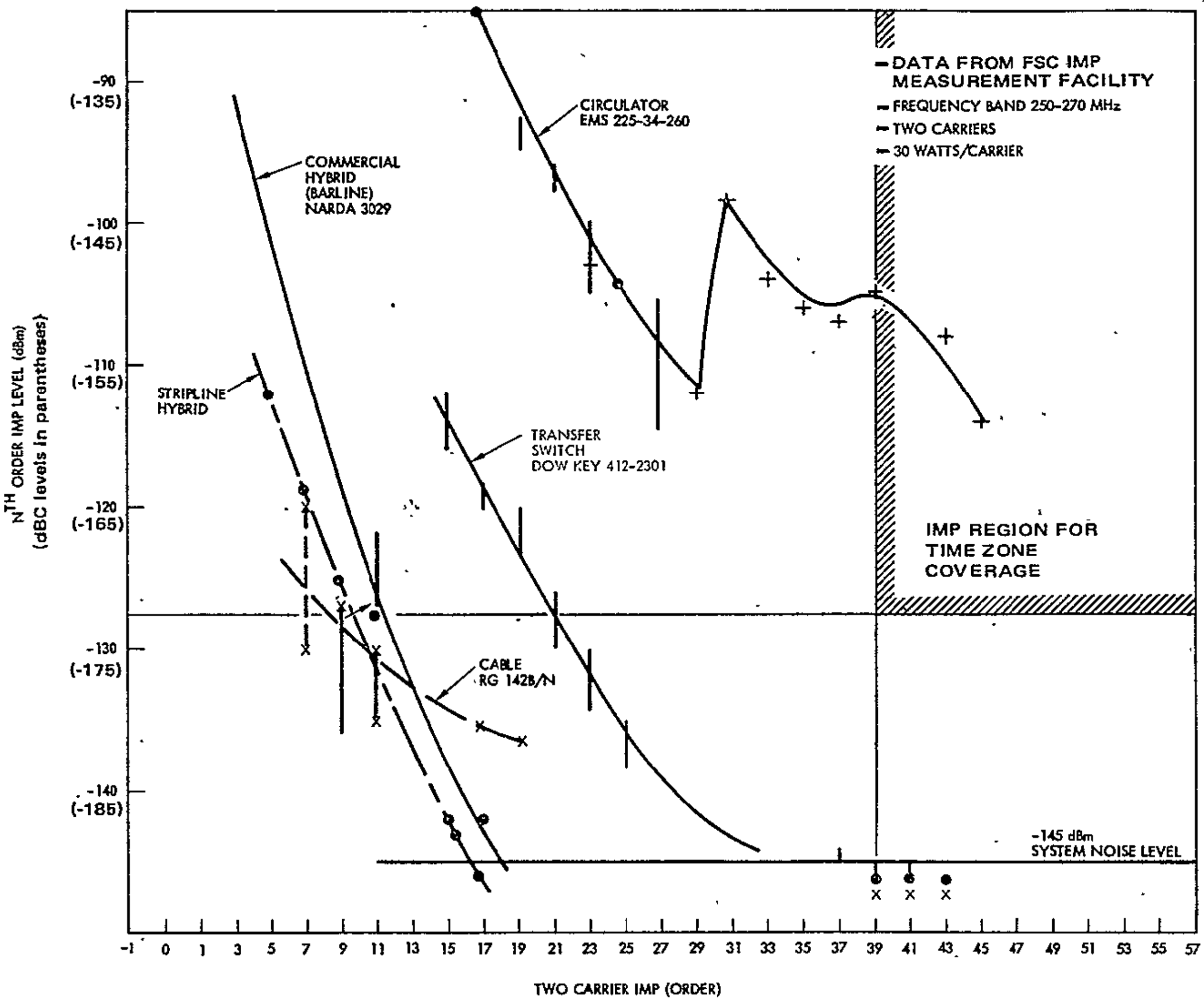


Figure 5-5. Intermodulation Products Generated from Passive Components

variation in device models, it is difficult to bound the IMP level and to say definitely that there is no IMP problem. Hence, at this stage of system definition IMP is recognized as a potential problem to be treated in future systems analyses.

Table 5-7 is a general set of hardware design guidelines derived from the IMP evaluation experience.

Table 5-7. General Hardware Design Guidelines for Minimizing Passive IM Products

• Emphasize Use of: • High Pressure Joints • High Temperature Solders and Welds • Extremely Smooth Finishes • Linear Dielectrics • Use With Caution: • Soft Solders • Platings and Other Surface Treatments • Dissimilar Metal Junctions • Carbon/Graphite Materials	• Avoid: • Ferromagnetic Materials • Gasketed Joints • Contaminated/Imperfect Materials • Tuning Screws • High Current Densities/Voltage Gradients • Critical Multipaction Dimensions

Finally, it is worth mentioning that device nonlinearities affect all the multiple access schemes (FDMA, TDMA and CDMA) by causing IMP generation or out-of-band spectrum spillover from a strong transmitter into a relatively weak received uplink.

5.8 MULTIPACTION

Multipaction is a secondary electron resonance which can occur in rf devices when the pressure is sufficiently low that the electron mean free path is longer than the distance between two electrodes. The electrode surfaces (or surface since multipaction can occur with a single electrode and an electrostatic field) must have a secondary emission coefficient greater than one. The frequency-geometry-power or voltage conditions must be such that the resonance will be sustained.

Multipaction susceptibility can be analyzed by referring to fd versus power or voltage curves where f is the frequency in MHz and d is the distance between electrodes. A typical curve for parallel electrode multipaction is shown in Figure 5-6. This is taken from JPL Technical Report 32-1500, "Final Report on RF Voltage Breakdown in Coaxial Transmission Lines, R. Woo, October 1, 1970, undertaken after encountering problems in a 60-watt transmitter at 960 MHz on the Ranger program.

TRW has recently experienced potential multipaction problems on FLTSATCOM program with a number of solid state amplifiers combined in a multicoupler feeding the transmit antenna. Frequencies are in the 250 MHz range and total transmit power exceeds 300 watts. For FLTSATCOM, the remedy used was to pressurize the output multicoupler.

We understand from private conversations with NASA that multipaction problems were experienced on ATS-6 at UHF with the output transmitters whose power output is 90 to 110 watts.

For PSCS, there is a potential multipaction problem in the transmitter output circuitry using the 300 watt amplifier. An obvious advantage of the multiple zone schemes is the use of much lower power per output circuit, hence probably eliminating the multipaction problem.

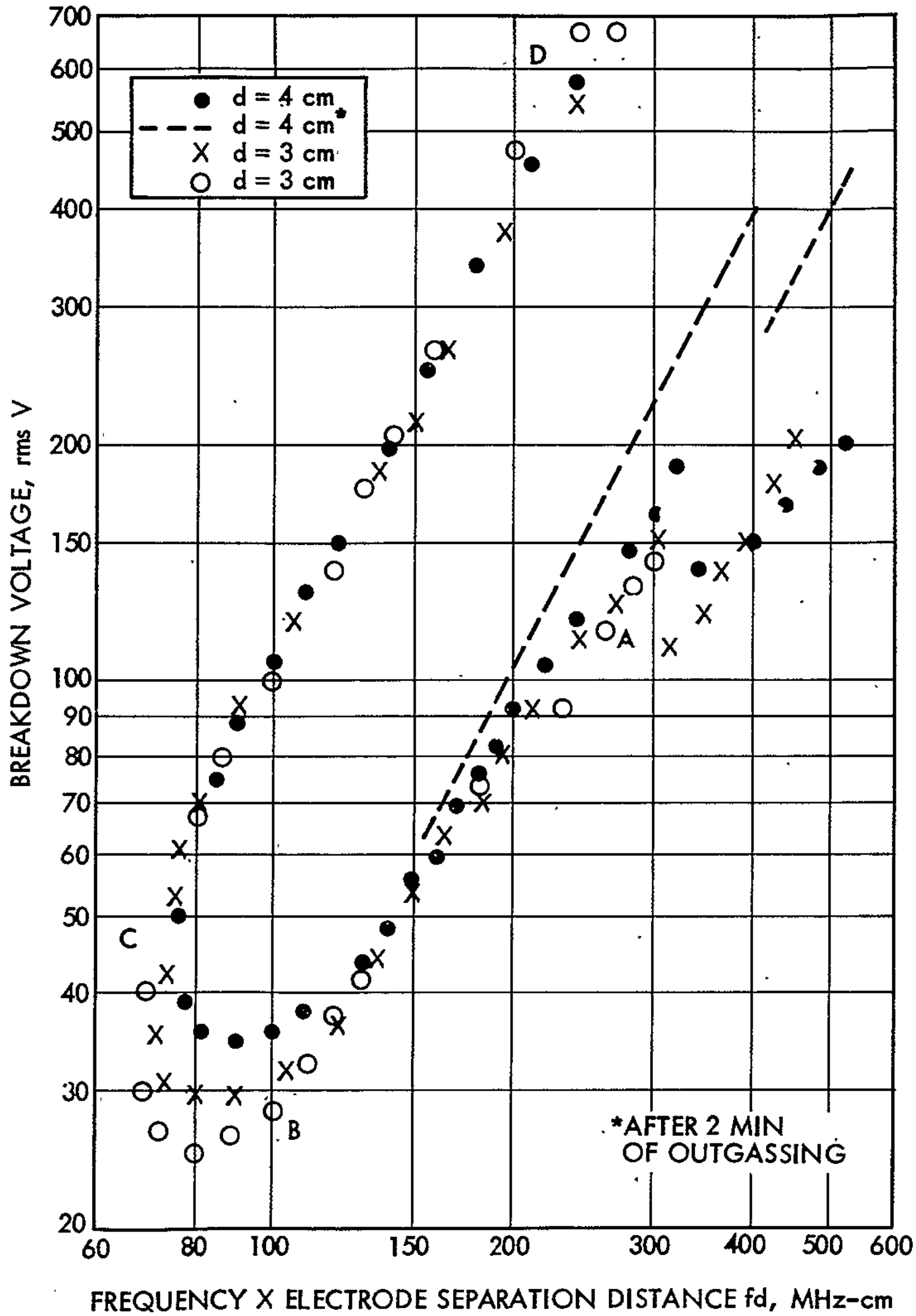


Figure 5-6. Multipacting Region for Parallel Electrodes

6. TERMINAL CONFIGURATIONS

6.1 FDMA TERMINAL WITH DEMAND ACCESS SIGNALING

Shown in Figure 6-1 is a block diagram of the proposed FDMA terminal employing demand access capability. This is to be considered the deluxe version of the MMACS terminal, and has considerable communications flexibility. The use of a network control station is required in order to assign communicating terminals to their proper frequencies.

Referring to the diagram, note that two antennas are used to achieve polarization diversity between transmit and receive modes. This avoids need for a diplexer and provides additional isolation in the full-duplex mode. These are four-arm conical spirals wound in opposite senses to achieve opposite direction circular polarization (Reference 23). The antennas are fed so as to produce an inverted cone-shaped beam with null at the zenith. Dimensions are selected to maximize the gain at a 30 to 60° elevation angle. Calculations show a gain of about 6 dB should be obtainable.

If a single antenna is preferable, a diplexer can be used to achieve transmit/receive band isolation with roughly no change in parts cost. This approach may be desirable if antenna mounting space is restricted. It is reasonable to expect a significant loss of transmit/receive isolation as compared to separate antennas, however. Additionally, since the diplexer is expected to have about 1 dB higher insertion loss than the standard front-end filter it replaces, the receiver noise figure is alos degraded by 1 dB. A third alternative is to wind 2 spirals (with opposite sense) onto a common cone. This would result in space savings, but perhaps at reduced transmit/receive isolation.

Since a narrow (less than 5 MHz) channel bandwidth is required, the conical spiral is actually greatly truncated, and has very little taper. At 800 MHz the antenna would be about 8 inches long and 6 inches in diameter at the base, and at 1600 MHz, the size would be reduced to 6 inches long by 4 inches in diameter.

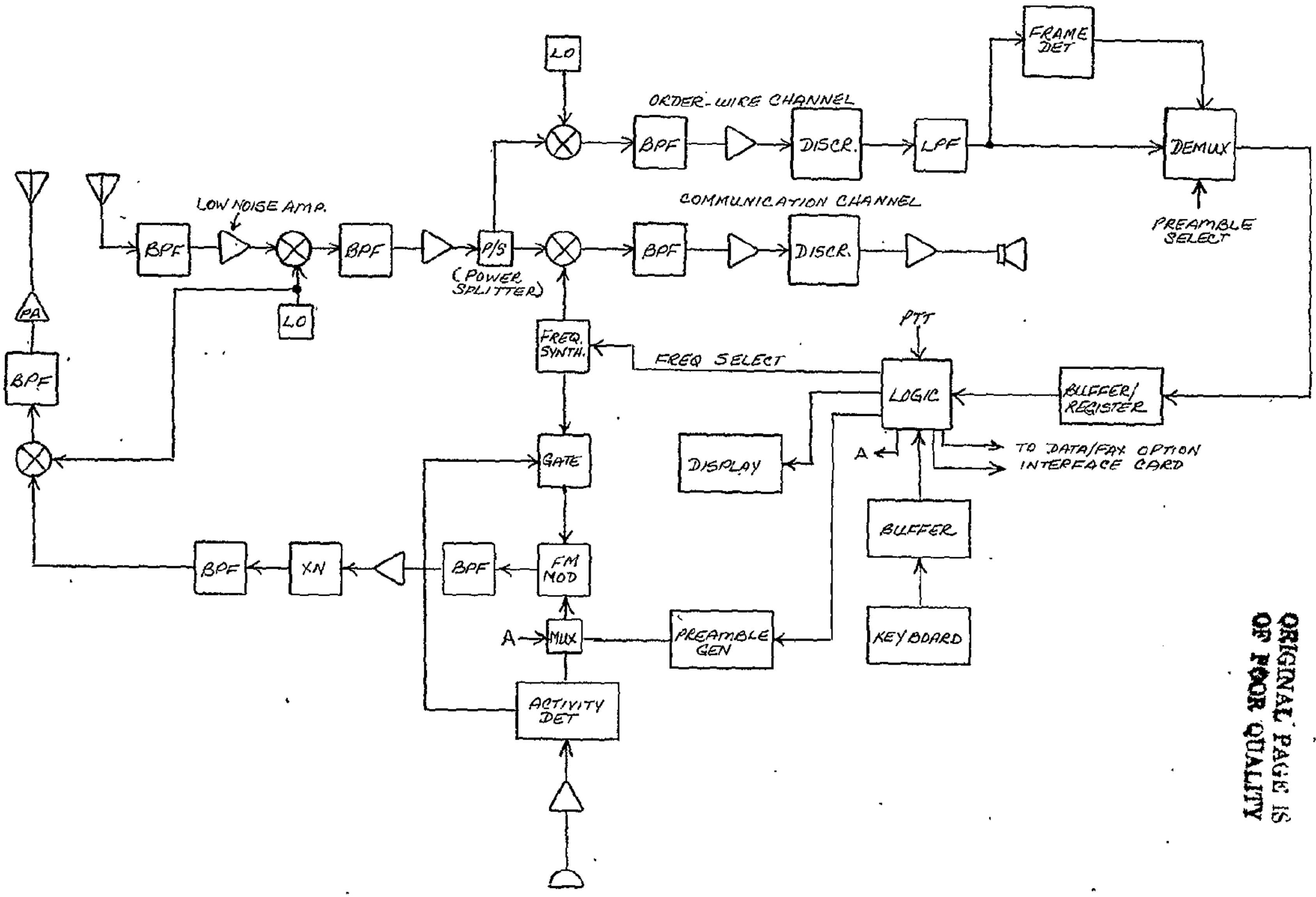


Figure 6-1. FDMA Terminal, Type I (With order-wire demand access).

Following the receive antenna is a low-noise front-end employing a high quality RF transistor. Achievable noise figures are currently 1.3 to 1.5 dB at UHF, and 1.9 to 2 dB at L-band. A dual-conversion IF strip then follows. Crystal filters are used at standard IF frequencies and provide a pre-detection bandwidth of 25 KHz. A standard FM discriminator is used for analog FM demodulation.

A parallel fixed frequency channel is used to receive TDMA downlink order-wire commands from the network control station. The 2.4 kilobit PCM-FM order-wire data is also demodulated in an FM discriminator. Frame synchronization is then obtained from a frame detector and demultiplexing is accomplished by the receiver recognizing its unique address preamble. The order-wire commands are then buffered and stored. Decoding and control logic processes the command information, controls the frequency synthesizer, and displays the assigned channel.

In the transmit mode, the terminal operator enters the address of the desired recipient on a numerical keyboard. The decoding and control logic processes this address and generates the address preamble of the desired recipient. The request message is transmitted when the operator presses the push-to-talk switch. When the network control station indicates (via the down-link oorder-wire channel) that the recipient is ready to receive the message, the sender may begin speaking into the microphone. The analog voice information is amplified and passed to an activity detector which gates the carrier on the presence of the user's voice. The analog audio is then FM modulated onto the carrier which is frequency multiplied and upconverted before final amplification. The final power amplifier provides 30 to 40 watts of RF power to the transmit antenna.

6.2 FIXED ASSIGNMENT FDMA TERMINAL

Figure 6-2 shows the fixed channel version of the FDMA terminal. This terminal is similar to the previous full-feature version except that it lacks an order-wire channel and control logic. Compatible with current fixed network operating practices such as those of police and fire departments, this terminal provides a less complex, lower cost alternative to

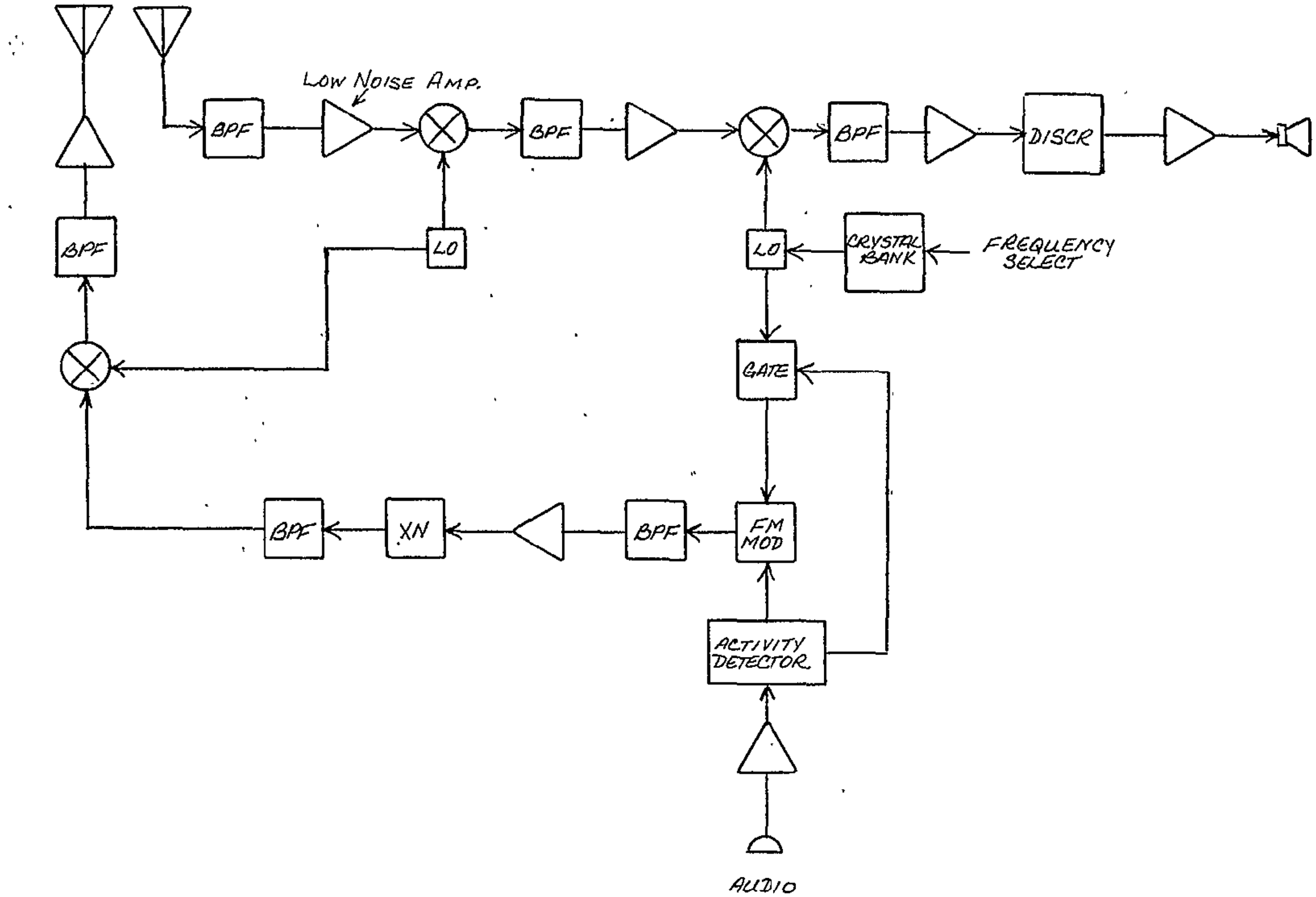


Figure 6-2. FDMA Terminal, Type II (Without order-wire)

full demand access operation. Since only a few channels are needed by the user of such a terminal, a bank of crystals is used in lieu of a frequency synthesizer. Like the full-feature terminal, this terminal also employs a voice-activated carrier and separate antennas for receive and transmit.

6.3 FDMA PAGING TERMINAL

This terminal, shown in Figure 6-3, is designed for receive-only paging services. It is assigned to a fixed frequency and uses an IF strip similar to those of the previous two designs. Multiple access among a large number of paging terminals is achieved through the use of various tone frequencies. Each unit contains a tone detector which recognizes only its unique tone and generates an audible paging signal. This unit is similar to current commercial pagers.

6.4 DATA/FACSIMILE OPTION FOR FDMA TERMINAL

Either the demand access or the fixed assignment terminal may be adapted for data/facsimile message handling. This is achieved by adding a Data/FAX interface card to the radio set. Mounted on a single plug-in board are the necessary converters and buffers required to interface a standard CRT or facsimile terminal to the radio set. Since the digital information is PCM-FM modulated, the same discriminator and FM modulator can be used for both voice and data. The output of the discriminator is buffered and passed to a register/decoder which translates the information into the language used by the data terminal (See Figure 6-4). Conversely, data entered from the terminal is buffered and converted, buffered again, and passed to the FM modulator for transmission. In the demand access terminal, the reception and transmission of digital data would be under the control of the decoding and control logic.

6.5 VEHICLE-MOUNTED, PORTABLE, AND HAND-HELD TERMINALS

Each of the three proposed configurations of the mobile terminal find counterparts in contemporary commercial FM radios. Like current radio sets, the vehicle-mounted terminal could operate from the 12 VDC automobile

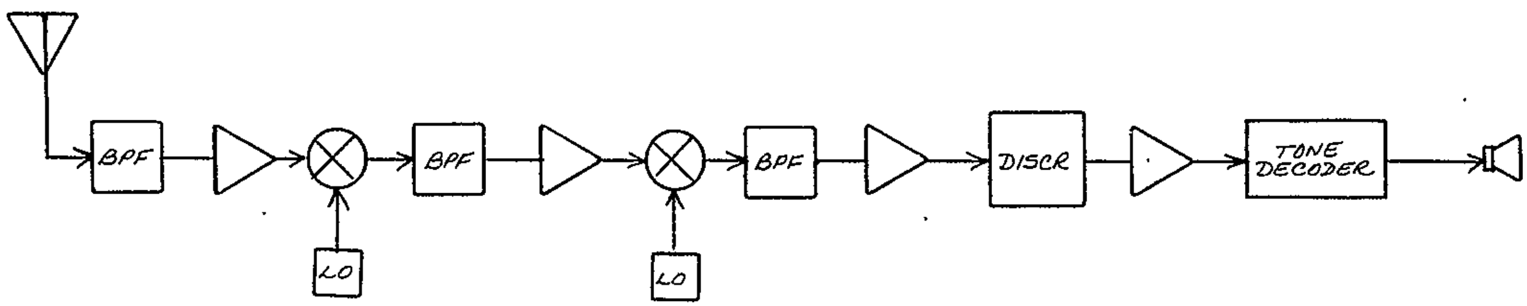
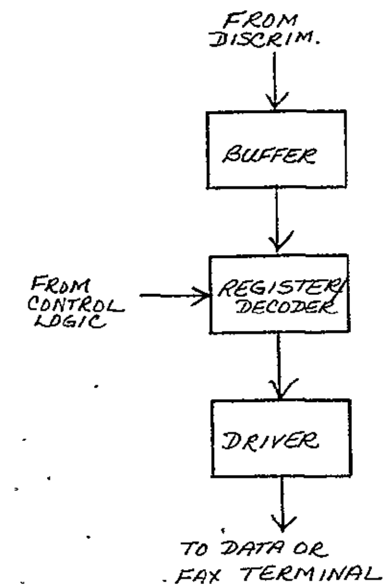
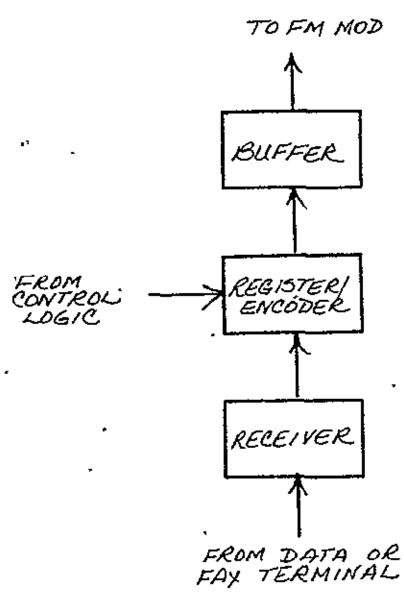


Figure 6-3. FDMA Paging Terminal



(a) Receiver



(b) Transmitter

Figure 6-4. Data and Facsimile Option Interface Card

supply. Power transistors now used for RF output stages operate directly from 12 volts and provide adequate power levels at efficiencies of 50-60% at 800 MHz and 45-55% at 1600 MHz. The vehicle-mounted terminal would be slightly larger than current sets in order to accommodate the extra RF equipment, logic, and signal processing components, but would meet the same environmental performance requirements. Two modified conical antennas, specially designed for vehicular use, would be roof-mounted base downward, extending 6-8 inches above the car. If flush mounting is desired, cavity-backed planar spiral antennas could be used instead, and would extend 2-4 inches into the passenger compartment.

An alternative package for the FDMA terminal would be a backpack or briefcase portable. Roughly the same size as the vehicular version, the portable would use the same circuit boards and subassemblies. Additionally, it would require a rechargeable battery power supply as a strap-on. A portable antenna stand would be used for rapid set-up of the transmit/receive antenna.

A third configuration has been examined, but involves greater technical risk. This would be a hand-held radio similar to today's commercial handi-talkies. The use of off-the-shelf components would preclude the production of this configuration in any version but the fixed frequency type terminal (Figure 6-2). Large-scale integration (LSI) could be used to condense the logic required to implement the demand access and digital data interface options into the hand-held terminal if desired. Present day hand-held radios are limited to about 5 watts output power, using devices with DC-RF efficiencies of roughly 50%. Since increasing the output power would require both higher capacity (i.e., larger) batteries and greater heat dissipation capability, this also becomes a limiting factor. Currently available components thus restrict the terminal to low complexity and low RF output power.

6.6 TDMA TERMINAL

Shown in Figure 6-5 is the block diagram of the candidate TDMA MMACS terminal. Consistent with the time division multiplexing scheme, a digital

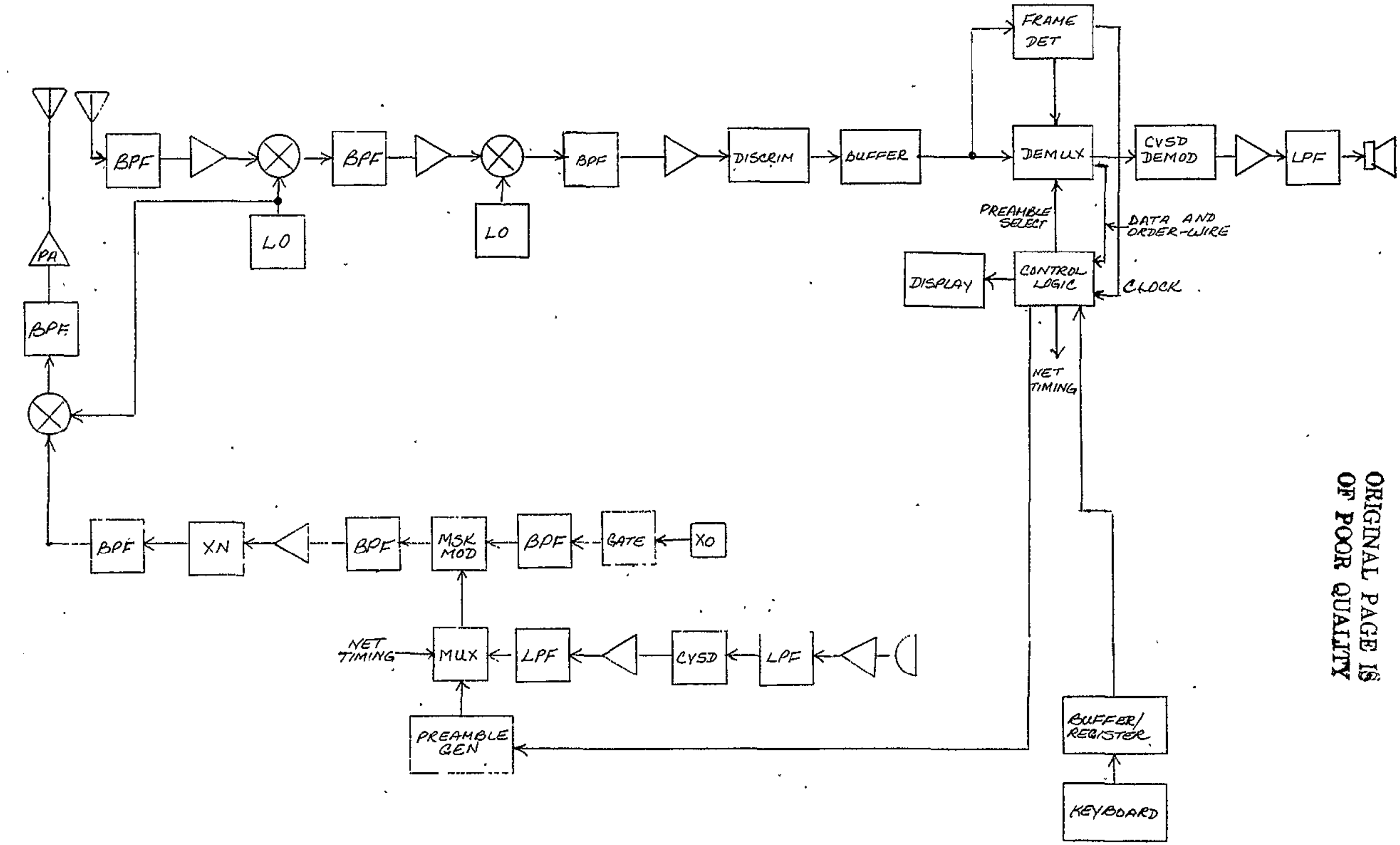


Figure 6-5. TDMA Terminal

modulation format is used. Selected for this application is minimum-shift keying (MSK), a form of spectrum conserving modulation, which can be described as continuous-phase PCM-FM with a modulation index of exactly 0.5. While MSK can be non-coherently demodulated using a standard frequency discriminator, the MSK modulator is more complex than for FSK or PSK. The savings in RF bandwidth over conventional techniques such as QPSK are considered worthwhile.

The receiver IF section is similar to that of the FDMA terminal, but has a much wider bandwidth. If a data burst rate of 500 kHz is assumed, then an IF bandwidth of on the order of a megahertz is required. The MSK-modulated carrier is demodulated by a frequency discriminator. Since the TDM frame contains both order wire and communications information, a frame detector and demultiplexer must be used to separate the two. Communications data is then passed to a CVSD demod and audio channel, while order-wire commands go to the terminal control logic. Information contained in the order wire data includes preamble select commands, net timing (transmit burst time) commands, and address of the party with whom currently communicating.

For transmission, audio from the microphone is amplified, filtered, and digitized in a CVSD digitizer. The voice data is stored and multiplexed with the address preamble of the intended recipient, then transmitted as bursts during the transmitter's pre-assigned time slot. Voice digitizing is done using the Continously Variable Slope Delta Modulation (CVSD) technique which has been selected for military tactical communications use. Both modulation and demodulation is done in a single integrated circuit (see Figure 6-6). Such chips are available both from Harris Semiconductor and Motorola.

The transmitter is similar to the FDMA transmitter except that an MSK modulator and wider bandwidth are used. Two different MSK modulators could be used for the mobile terminal application, differing in complexity and flexibility. The first type is a slightly modified version of a Brady modulator (Reference 24) shown in Figure 6-7. While it requires considerable hardware to implement, its flexibility allows it to be used at

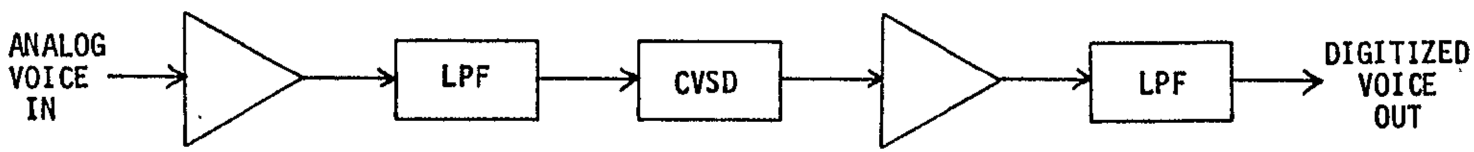


Figure 6.6. CVSD Voice Digitizer

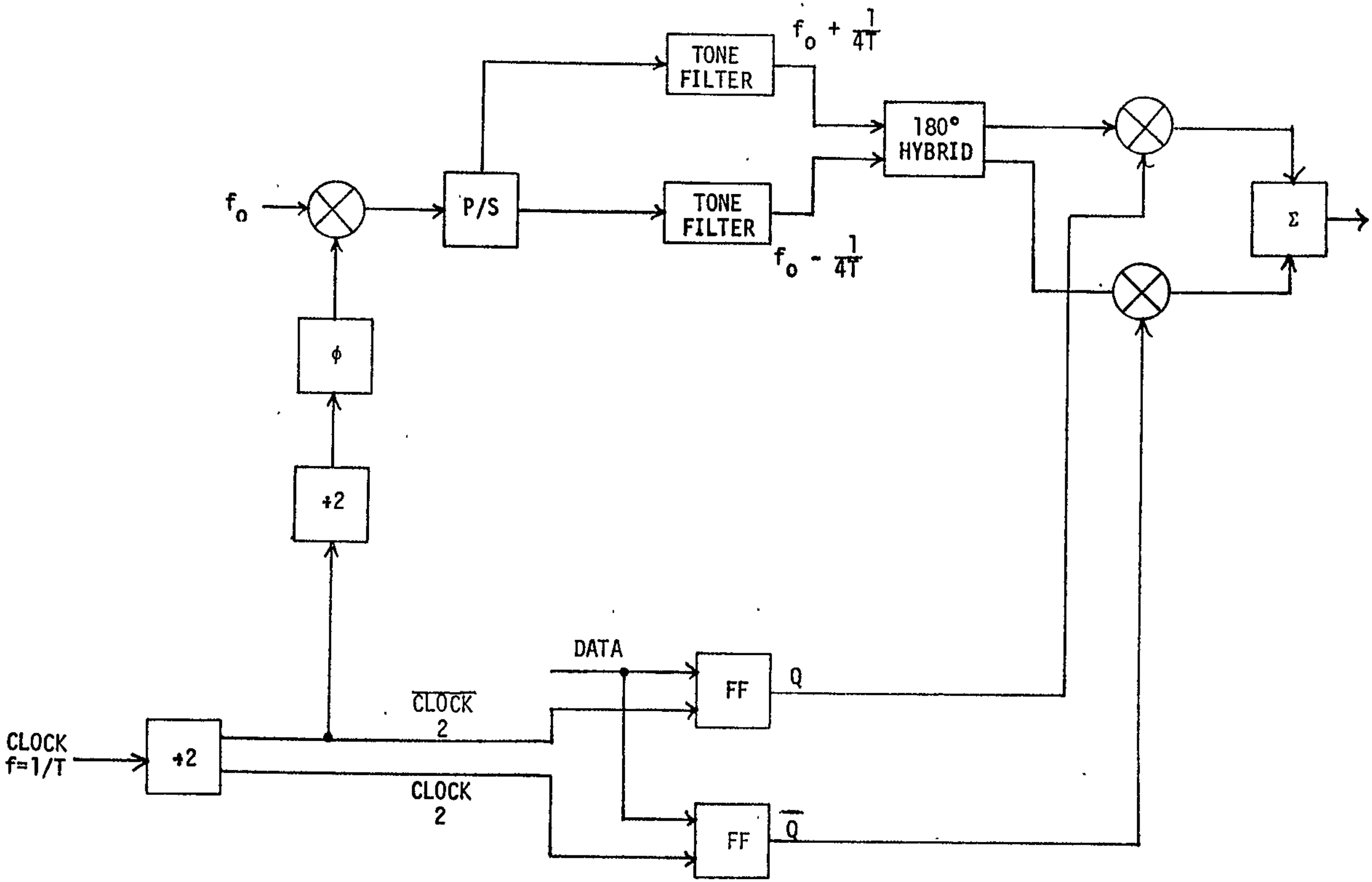


Figure 6-7. MSK Modulator

varying data rates. An alternative to the Brady modulator is a TRW proprietary scheme which uses a bi-phase modulator and sync function filter. This scheme requires much less hardware, but is suitable only for a single data rate. However, this method may still be desirable when only a few data rates are used.

Because of the high peak-to-average power ratio, a power amplifier suitable for pulsed transmission must be used. Assuming a TDMA scheme for 20 users with a 0.4-sec frame time, each user will transmit for on the order of 13 ms with a duty cycle of on the order of three percent. Since thermal time constants for current pulsed high power RF transistors are on the order of 200 to 300 sec, thermally speaking the device is operating in a CW mode for a 13 ms pulse width. Therefore, CW power transistors are required for this application. Since current power limits for these devices are less than 50 watts, multiple devices are required for higher power levels. These factors place severe limits on the achievable performance of the TDMA system.

6.7 CDMA TERMINAL

A CDMA terminal is diagrammed in Figure 6-8. In this system, direct-sequence pseudorandom noise (PN) code modulation is used to generate a spread spectrum signal. Multiplying by a PN code which is an exact replica of the code used in the transmitter is required to demodulate a received signal, and only the received code multiplied by the matching PN code will be recovered. Multiple access capability is achieved by assigning each user a unique code. Since the PN code rate greatly exceeds the data rate a much wider-band signal is tansmitted.

Therefore, a much wider IF bandwidth is required in the receiver than with FDMA or even TDMA. The actual IF bandwidth is on the order of the PN code rate. For this case, assume this rate to be roughly 5 MHz. Since digital data is required, CVSD voice digitization and MSK modulation is used, as in the TDMA system. Also like the TDMA system, a separate order-wire channel is used to carry the spacecraft clock signal.

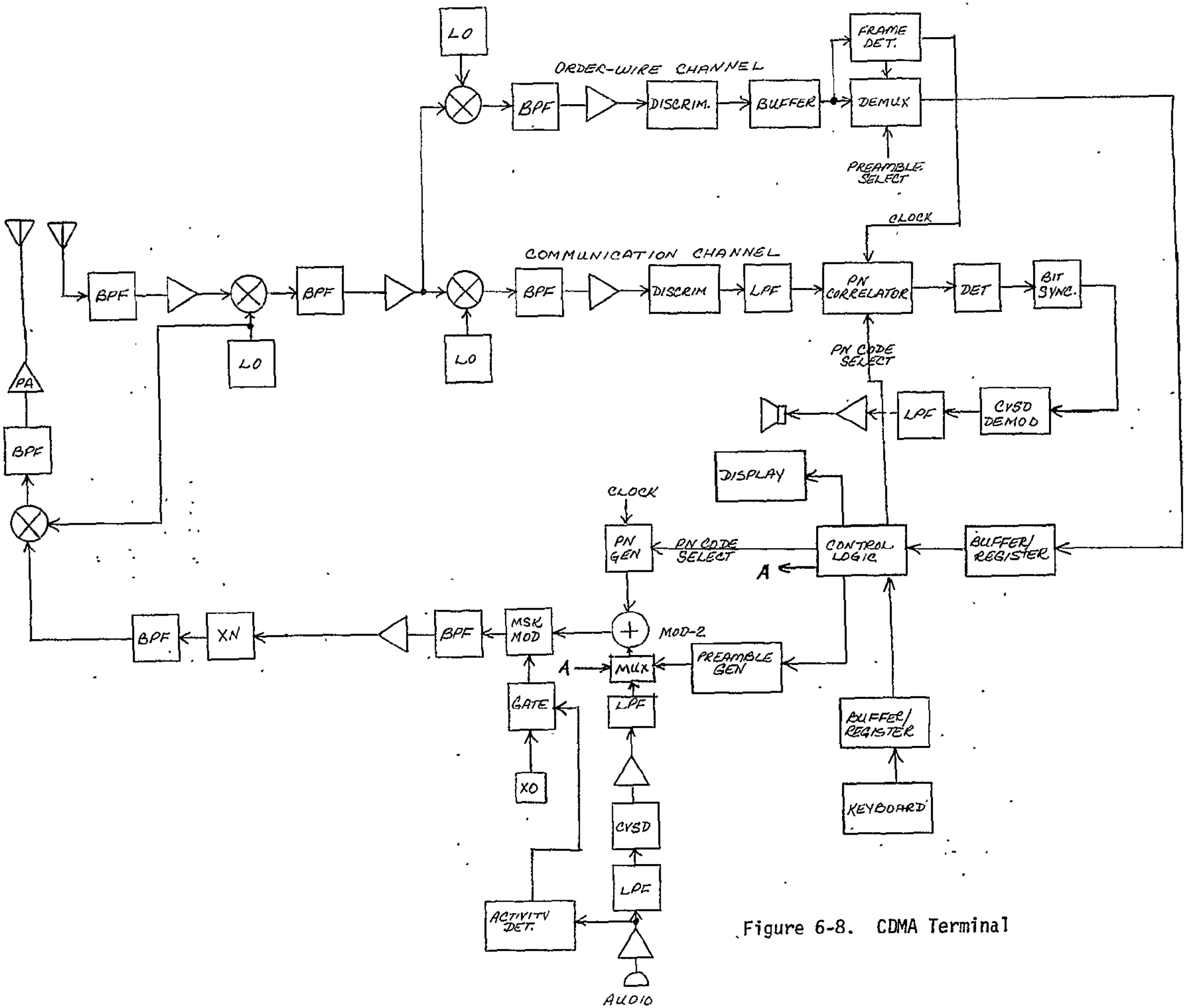


Figure 6-8. CDMA Terminal

Demand access signaling information is also obtained from the downlink order-wire channel, as in the FDMA and TDMA systems. Here, the network control station assigns the PN codes to be used for receiving and transmitting. The user can dial the number of the intended recipient, and also see the number of the party to which he is talking on a display, as a check.

Probably the key item in the CDMA terminal is the PN code correlator. PN code acquisition loops using both active and passive correlators appear to be feasible for the portable terminal. Active correlation is advantageous in that it uses off-the-shelf components and can conceptually be applied to both analog and digital modulation systems. The major drawback to the active correlator is the significant time required for code synchronization.

Shown in Figure 6-9 is a possible implementation of an active correlator. Code correlation is performed in a double-balanced mixer. The bandpass filter is chosen to maximize the SNR at the data rate(s) of interest. The signal is then amplified, square-law detected, low-pass filtered, and integrated. If the local and received PN codes are uncorrelated, the integrator output falls below threshold and the local code is shifted in phase a fraction of a chip and correlation again attempted. After correlation is achieved, correct PN code tracking is accomplished by driving the local PN generator with the clock derived from the downlink order-wire channel. Except for the mixer and bandpass filter, all the active PN acquisition circuit would be constructed using integrated circuits.

It is worthwhile to consider the application of a passive correlator for PN despreading. Passive correlation would greatly reduce the problem of code synchronization, nearly eliminating long acquisition times. However, the passive correlator is compatible with only binary modulation formats.

Passive correlators, also called matched filter synchronizers, are actually delay lines made up of a number of delay elements, each of which has a time delay equal to the period of the PN code clock. The number of

C - 2

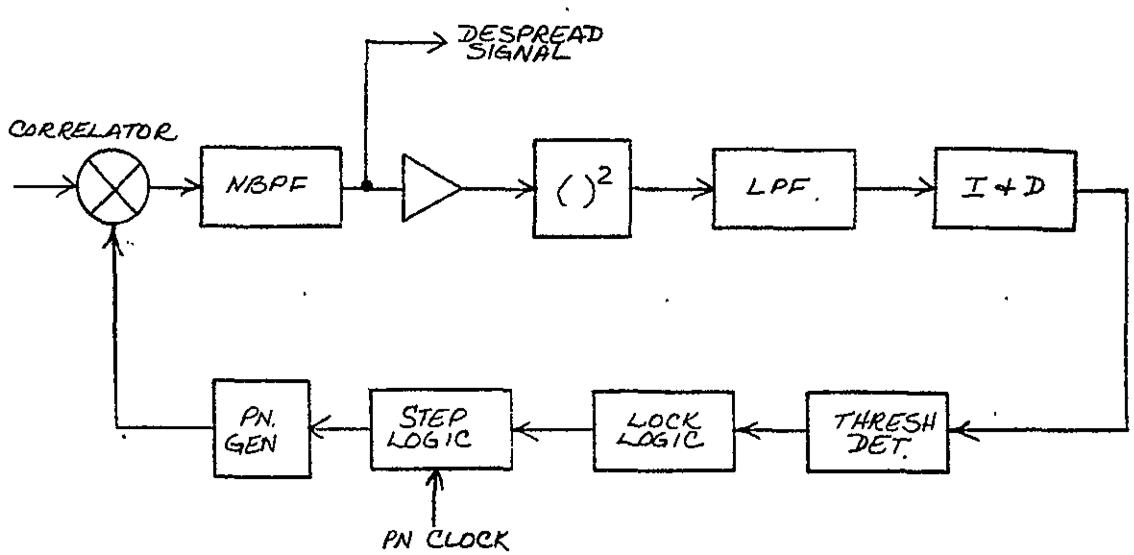


Figure 6-9. PN Code Acquisition Loop with Active Correlator

elements is equal to the length of the PN code. The passive correlator can recognize a particular code sequence determined by the tap settings, as shown in Figure 6-10. The received sequence is shifted through the delay line, and, at the correct phase, all "ones" will appear at the elements selected by the upper taps and all "zeros" at the lower taps. The zero samples are then inverted and thus add constructively to the "ones" samples, producing a positive output.

Such a correlator may be implemented either at baseband or IF. A convenient implementation at baseband is shown in Figure 6-11, in which all digital information with an MSK modulation format is assumed. The use of a frequency discriminator to demodulate the MSK is expedient since the absolute polarity of the data is automatically determined. A digital shift register is then required to correlate the signal, and could likely be implemented using charge-coupled devices (CCDs) and LSI, in order to conserve power and size.

If the passive correlator is implemented at IF, the configuration would be as shown in Figure 6-12, using a surface acoustic wave (SAW) tapped delay line. However, at IF the absolute polarity of the data cannot be determined, and thus separate PN codes for data one and data zero must be sent. One of the SAW correlators will "ring up" depending on whether one or zero is sent. The output of each correlator is detected, the two are summed, and then the sum is sampled near the peak (or null in the case of data zero) to produce an NRZ data stream.

Regardless of the passive correlator design chosen, the correlator can only be used at a unique PN code rate, since the elemental time delays must be equal to the period of the PN clock. Since no appreciable doppler is anticipated in the MMACS application, this should not be a problem.

Like the receiver IF, the transmitter chain must also be wideband in order to pass the spread spectrum signal. The transmitter is virtually the same as in the TDMA terminal except that the high rate PN code is modulo-2 added to the data before it is modulated onto the carrier. Note that, however, while in the TDMA system the power amplifier operates in a pulsed mode, the PA in this CDMA system must operate in a CW mode.

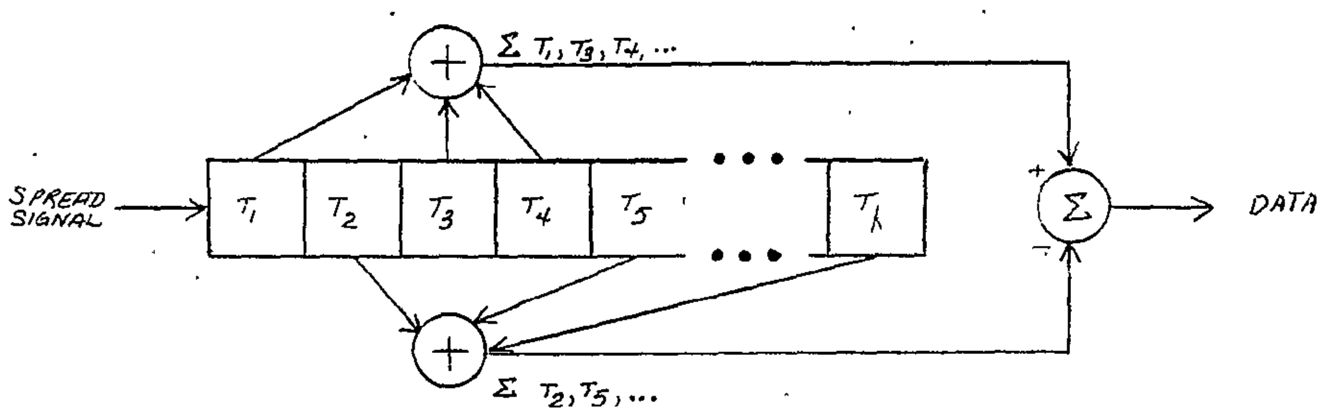


Figure 6-10. Passive (Delay Line) Correlator

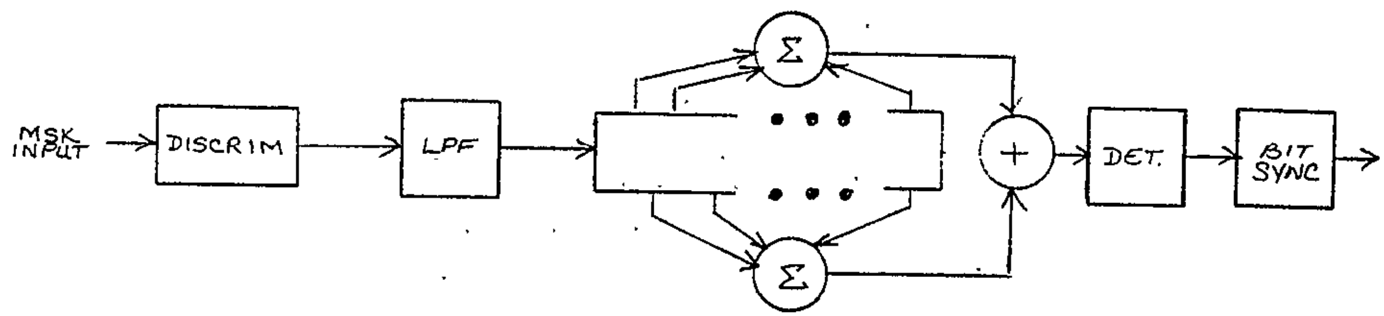


Figure 6-11. Baseband Passive Correlator

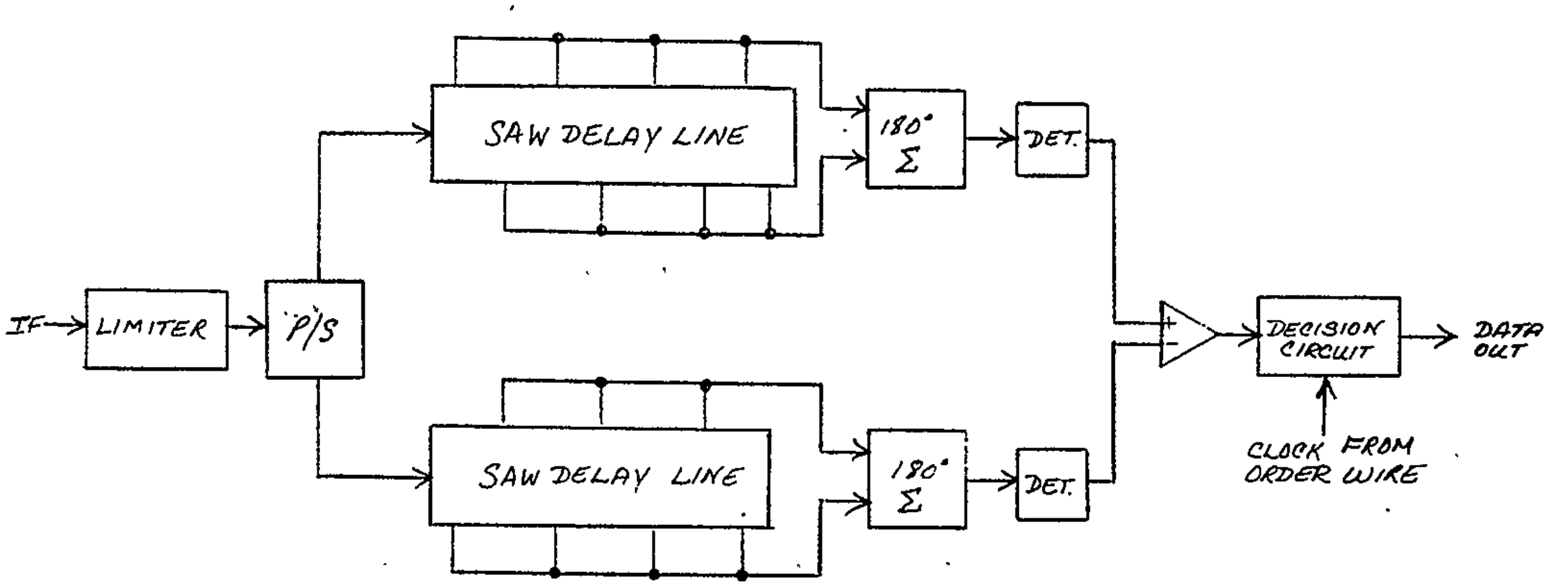


Figure 6-12. IF Passive Correlator

6.8 PARTS COST ESTIMATES

6.8.1 Assumptions and Ground Rules

Conservative parts cost estimates have been made for the various ground terminal options and are based on the following assumptions:

1) Parts are off-the-shelf with no special quality assurance testing required.
2) Operating temperature range is -30°C to +70°C.
3) Parts pricing quantity ≥1000 pieces.
4) Printed circuit board construction for both RF and logic circuits.
5) Prices based on quotes, catalogs, and current experience.

6.8.2 FDMA Terminal

Parts cost estimates are shown in Tables 6-1 to 6-3 for each of the FDMA terminal options. Note that the costs for the data and facsimile interface option in Table 6-4 are for the interface card only, and must be added to the cost of the FDMA Type I or Type II terminals when the data/FAX option is installed.

6.8.3 Packaging Options

Several combinations of features and packages are possible for the FDMA terminal, as shown below:

Feature / Package	Mobile	Backpack/ Briefcase	Hand-Held
Type I	X	X	
Type II	X	X	X
Paging	X	X	X
Data/Fax Option	X	X	

Table 6-1. FDMA Terminal - Type I (With Order-Wire Demand Access) ROM Parts Cost Estimate

Antenna, etc.	Quantity	Cost
Antenna	2	200
Frequency Synthesizer	1	100
Discriminantor	2	20
FM Modulator	1	30
LO, Crystal	2	50
Frequency Multiplier	1	20
Display	1	10
Gate	1	5
Activity Detector	1	5
Buffer	1	10
Power Splitter	1	10
Amplifiers		
Power Amplifier	1	100
Audio	2	10
RF Front End	1	100
RF	3	75
Mixers		
Double-balanced	4	60
Filters		
BPF - Crystal	4	100
BPF	3	45
LPF	1	5
Logic		
Frame Detector	1	
Demultiplexer	1	
Control Logic	1	75
Buffer/Register	1	
Preamble Generator	1	
Support Equipment		
Microphone	1	20
Speaker	1	5
Battery (not in mobile unit)	1	20
Switches and Jacks		20
Boards		20
Hardware		50
Keyboard		5
	Total	$1,170
		$1,200

Table 6-2. FDMA Terminal - Type II (Without Order-Wire) ROM Parts Cost Estimate

Antenna, etc.	Quantity	Cost
Antenna	2	200
Crystal Bank (4 ch x 2 crystals/ ch = 8 crystals)		24
Discriminator	1	10
FM Modulator	1	30
LO, Crystal	2	50
Frequency Multiplier	1	20
Gate	1	5
Activity Detector	1	5
Amplifers		
Power Amplifier	1	100
Audio	2	10
RF Front End	1	100
RF	3	75
Mixers		
Double-balanced	3	45
Filters		
BPF - Crystal	3	75
BPF	3	45
Support Equipment		
Microphone	1	20
Speaker	1	5
Battery	1	20
Switches and Jacks		20
Boards		20
Hardware		50
	Total	$900

Table 6-3. FDMA Paging Terminal ROM Parts Cost Estimate

Antenna, etc.	Quantity	Cost
Antenna	1	10
LO, Crystal	2	50
Discrimiantor	1	10
Amplifiers		
RF	2	50
Audio	1	5
RF - Front End	1	100
Mixers		
Double-balanced	2	30
Filters		
BPF - Crystal	3	75
Support Equipment		
Speaker	1	5
Battery	1	10
Switches and Jacks		10
Boards		15
Hardware		30
Tone Decoder	1	5
	Total	$405
		$400

Table 6-4. Data and Facsimile Option Interface Card ROM Parts Cost Estimate

	Quantity	Cost
Buffer	2	20
Register/Decoder	1	20
Register/Encoder	1	20
Driver	1	10
Receiver	1	10
Board	1	10
	Total	$90
		$100

Vehicle-mounted and backpack radios would use common boards as a practical cost-savings step, and so no appreciable cost difference results. For the Type II radio, a hand-held version is also possible, and would require different boards and parts to achieve a higher component density. However, since for high quantities the cost of parts alone is a major part of the total cost, there should be no appreciable difference in the overall costs of the hand-held and mobile units. Only one packaging style is required for the paging terminal, which could be used for both vehicle-mounted and portable applications.

6.8.4 TDMA and CDMA Terminals

Estimated parts costs for full-feature TDMA and CDMA terminals are shown in Tables 6-5 and 6-6. These are about 30 percent higher than those for the FDMA equivalent, and reflect the increased complexity required with these approaches. The handheld packaging option was not considered for these terminals.

6.8.5 Summary Of Parts Costs

The parts cost estimates are summarized in Table 6-7. The demand-access FDMA terminal estimate is $1,200. The TDMA and CDMA terminals (which are assumed demand access) are about 30% more expensive due to the increased complexity.

Table 6-5. TDMA Terminal - (With Order-Wire Demand Access) ROM Parts Cost Estimate

Antenna, etc.	Quantity	Cost
Antenna	2	200
Discriminator	1	20
Buffer	1	10
CVSD Modem	2	30
MSK Modulator	1	75
Multiplier	1	20
LO-Crystal	3	100
R,L,C		100
Activity Detector	1	5
Gate	1	5
Display	1	10
Amplifiers		
RF	3	100
RF Front End	1	100
PA	1	100
Audio	3	15
Mixers		
Double-Balanced	3	30
Filters		
BPF - Crystal	1	25
BPF	6	140
LPF	3	15
Logic		
Frame Detector	1	30
Demultiplexer	2	100
Multiplexer	1	30
Preamble Generator	1	10
Buffer/Register	2	40
Control Logic	1	50
Support Equipment		
Microphone	1	20
Speaker	1	5
Battery	1	20
Switches and Jacks		20
Boards		20
Hardware		50
Keyboard		5
	Total	$1600

Table 6-6. CDMA Terminal (With Order-Wire Demand Access) ROM Parts Cost Estimate

Antenna, etc.	Quantity	Cost
Antenna	2	$200
Discriminator	2	20
Buffer	1	10
CVSD Modem	2	30
MSK Modulator	1	75
LO-Crystal	4	100
Phase Detector	1	15
VCO	1	15
Detector	1	5
Activity Detector	1	5
Gate	1	5
Display	1	10
Multiplier	1	20
R,L,C	1	100
Amplifiers		
RF Front End	1	100
Power Amp	1	100
Audio	3	15
RF	4	100
Mixers		
Double-Balanced	4	60
Filters		
BPF	7	140
LPF	4	20
Loop	1	5
Logic		
Bit Synch	1	20
PN Generator	1	20
Modulo-2 Adder	1	5
Control Logic	1	50
Preample Generator	1	10
Buffer/Register	2	40
Frame Detector	1	30
Demultiplexor	1	50
PN Correlator	1	100
Support Equipment		
Microphone	1	20
Speaker	1	5
Battery	1	20
Switches and Jacks		20
Boards		20
Hardware		50
Keyboard		5
	Total	$1600

Table 6-7. Summary of ROM Parts Cost Estimates

Terminal	Type*	Cost Estimate
FDMA	I	$1,200
	II	900
	Paging	400
TDMA	I	$1,600
CDMA	I	$1,600

*Type I = Full Order-Wire Demand Access Capability
Type II = Fixed Channel Assignment

7. COST ESTIMATE

7.1 INTRODUCTION AND SUMMARY

In response to contract Statement of Work requirements, approximate costs have been estimated for quantities of 10 to 10,000 terminals in each of 11 potential configurations. A similar estimate was made for an "interface card" applicable to either mobile (vehicle mounted) or manpack FDMA configurations as an optional add-on accessory.

For <u>costing purposes only</u>, several of the potential configurations are either identical, exhibit negligible cost differences, or are characterized by relatively small cost variations which fall within the accuracy tolerance of the estimate. Thus, five sets of costs cover all eleven configurations. The cost estimate summary is presented in Table 7-1.

Table 7-1. Cost Estimate Summary

Cost Estimate Identification	Configuration Description	Unit Cost Estimate (10,000 Units)
A	FDMA, Type I, mobile (vehicle-mounted) FDMA, Type I, manpack FDMA, Type II, handheld	$1,900
B	FDMA, Type II, mobile (vehicle mounted) FDMA, Type II, manpack	$1,700
C	FDMA, handheld, paging only	$ 800
D	FDMA, interface card only	$ 200
E	TDMA, mobile (vehicle-mounted) TDMA, manpack CDMA, mobile (vehicle-mounted) CDMA, manpack	$2,500

The breakdown of the five estimates (A through E) by production quantities is presented in Tables 7-2 through 7-6. The basis for these estimates is discussed in the following sections.

Table 7-2. Estimated Costs for FDMA, Type I Terminals(with Order Wire) (Estimate "A")

Quantity		Estimated Unit Cost in K Dollars	
Release Qty.	Cumulative Qty.	Lot	Cumulative
First 10	10	13.8	13.8
Next 100	110	5.7	6.4
Next 400	510	3.0	3.7
Next 600	1,110	2.7	3.2
Next 1000	2,110	1.9	2.6
Next 4000	6,110	1.8	2.1
Next 4000	10,110	1.7	1.9

Table 7-3. Estimated Costs for FDMA, Type II Terminals(without Order Wire) (Estimate "B")

Quantity		Estimated Unit Cost in K Dollars	
Release Qty.	Cumulative Qty.	Lot	Cumulative
First 10	10	12.4	12.4
Next 100	110	5.1	5.8
Next 400	510	2.7	3.3
Next 600	1,110	2.4	2.9
Next 1000	2,110	1.7	2.3
Next 4000	6,110	1.6	1.9
Next 4000	10,110	1.5	1.7

Table 7-4. Estimated Costs for FDMA, Handheld (Paging Only) Terminal (Estimate "C")

Quantity		Estimated Unit Cost in K Dollars	
Release Qty.	Cumulative Qty.	Lot	Cumulative
First 10	10	5.5	5.5
Next 100	110	2.3	2.6
Next 400	510	1.2	1.5
Next 600	1,110	1.1	1.3
Next 1000	2,110	0.9	1.1
Next 4000	6,110	0.8	0.9
Next 4000	10,110	0.8	0.8

Table 7-5. Estimated Costs for Interface Cards (Estimate "D")

Quantity		Estimated Unit Cost in K Dollars	
Release Qty.	Cumulative Qty.	Lot	Cumulative
First 10	10	1.4	1.4
Next 100	110	0.6	0.6
Next 400	510	0.3	0.4
Next 600	1,110	0.3	0.3
Next 1000	2,110	0.2	0.3
Next 4000	6,110	0.2	0.2
Next 4000	10,110	0.2	0.2

Table 7-6. Estimated Costs for TDMA and CDMA Terminals (Estimate "E")

Quantity		Estimated Unit Cost in K Dollars	
Release Qty.	Cumulative Qty.	Lot	Cumulative
First 10	10	17.9	17.9
Next 100	110	7.4	8.3
Next 400	510	3.9	4.8
Next 600	1,110	3.5	4.2
Next 1000	2,110	2.5	3.4
Next 4000	6,110	2.3	2.7
Next 4000	10,110	2.2	2.5

7.2 BASIS FOR ESTIMATE

Prior to estimation of costs, a typical "straw-man" program was defined to provide a rational basis for costing. This program would apply to any of the types of terminals. The elements of the "straw-man" program include specification of test requirements, tooling, delivery rate, production techniques, attrition, inspection level, and parts level. These elements are outlined briefly in the following subsections.

7.2.1 Production Release and Schedule Plan

The "straw-man" program assumes quantity production in several lots within which manufacturing releases are anticipated. This plan, calling for four lots and a total of nine releases to produce, 10,110 deliverable units in 4.5 years is shown in Table 7-7. The first lot of 110 units consists of an experimental release of 10 units followed by a pilot run of 100 units to prove methods, tools, drawings, test equipment, and production techniques. The next releases of 400 and 600 units each will permit further refinement and production training prior to full large quantity commitment which follows.

Table 7-7. Production Release and Schedule Plan

Lot/Release	Production Release	Release Quantity	Year 1: 1	2	3	4	5	6	7	8	9	10	11	12
Lot 1	1	10	2	4	4									
Lot 1	2	100				10	15	15	20	30	70			
Lot 2	3	400									30	40	50	50
Lot 2	4	600												
Lot 2	5	1000												
Lot 3	6	2000												
Lot 3	7	1000												
Lot 4	8	1000												
Lot 4	9	2000												
Total Units Delivered	Monthly		2	4	4	10	15	15	20	30	40	40	50	50
Total Units Delivered	Cumulated		2	6	10	20	35	50	70	100	140	180	230	280

Lot/Release	Production Release	Release Quantity	Year 2: 13	14	15	16	17	18	19	20	21	22	23	24
Lot 1	1	10												
Lot 1	2	100												
Lot 2	3	400	60	60	70	40								
Lot 2	4	600			10	40	80	100	110	120	120	20		
Lot 2	5	1000										110	150	200
Lot 3	6	2000												
Lot 3	7	1000												
Lot 4	8	1000												
Lot 4	9	2000												
Total Units Delivered	Monthly		60	60	80	80	80	100	110	120	120	130	150	200
Total Units Delivered	Cumulated		340	400	480	560	640	740	850	970	1090	1220	1370	1570

Lot/Release	Production Release	Release Quantity	Year 3: 25	26	27	28	29	30	31	32	33	34	35	36
Lot 1	1	10												
Lot 1	2	100												
Lot 2	3	400												
Lot 2	4	600												
Lot 2	5	1000	250	290										
Lot 3	6	2000		10	300	300	300	300	300	300	190			
Lot 3	7	1000									110	300	300	300
Lot 4	8	1000												
Lot 4	9	2000												
Total Units Delivered	Monthly		250	300	300	300	300	300	300	300	300	300	300	300
Total Units Delivered	Cumulated		1820	2120	2420	2720	3020	3320	3620	3920	4220	4520	4820	5120

Lot/Release	Production Release	Release Quantity	Year 4: 37	38	39	40	41	42	43	44	45	46	47	48
Lot 1	1	10												
Lot 1	2	100												
Lot 2	3	400												
Lot 2	4	600												
Lot 2	5	1000												
Lot 3	6	2000												
Lot 3	7	1000	300	300	300	90								
Lot 4	8	1000				210	300	300	300	300	300	290		
Lot 4	9	2000										10	300	300
Total Units Delivered	Monthly		300	300	300	300	300	300	300	300	300	300	300	300
Total Units Delivered	Cumulated		5420	5720	6020	6320	6620	6920	7220	7520	7020	8120	8420	8720

Lot/Release	Production Release	Release Quantity	Year 5: 49	50	51	52	53	54	55	56	57	58	59	60
Lot 1	1	10												
Lot 1	2	100												
Lot 2	3	400												
Lot 2	4	600												
Lot 2	5	1000												
Lot 3	6	2000												
Lot 3	7	1000												
Lot 4	8	1000												
Lot 4	9	2000	300	300	300	300	190							
Total Units Delivered	Monthly		300	300	300	300	190							
Total Units Delivered	Cumulated		9020	9320	9620	9920	10110							

7.2.2 Nondeliverable Test Samples and Attrition

For the assumed production program to yield deliverable units as defined above, additional equipment must be produced, and included in the cost of deliverable units to provide for nondeliverable environmental test samples and attrition (life test units, loss, scrap, etc.). Thus, to provide a total of 10,110 units, costs have been included for actual production of 10,165, as detailed in Table 7-8.

Table 7-8. Total Quantity Requirements

Lot No.	Release No.	Deliverable Quantity	Environmental Test Samples	Attrition	Total Production
1	1	10	1	-	11
	2	100	2	3	105
2	3	400	3	3	406
	4	600	3	4	607
	5	1,000	5	5	1,010
3	6	2,000	5	6	2,011
	7	2,000	2	3	2,005
4	8	2,000	2	3	2,005
	9	2,000	2	3	2,005
Total		10,110	25	30	10,165

7.2.3 Testing, Test Equipment, and Tooling

The estimated costs presented here assume 100 percent acceptance testing; that is, each unit is tested rather than each release sampled. This acceptance testing includes a functional performance check and a limited burn-in.

Each environmental test sample specified in Paragraph 7.2.2 is assumed to have been subjected to temperature, vibration, handling/transportation shock, and humidity tests. A rough estimate of tooling and test equipment required is summarized in Table 7-9 and these items have been included as part of the estimated production costs.

Table 7-9. Tooling and Test Equipment Quantity Requirements

Tool/Test Set	Terminal Production Quantity Lot 1	Lot 2	Lot 3
Board assembly fixture	50	200	500
Harness assembly fixture	5	10	20
Connector extender	10	60	100
Final assembly fixture	5	25	50
Card assembly fixture	5	25	50
Unit/subassembly test set	2	3	10
Cable test set	1	2	4
Note: Quantities are cumulative.			

7.2.4 Manufacturing

Manufacturing costs are based on several assumed production techniques to provide "ground rules" for the quantity production estimates. These assumptions include:

- Design firm when released
- Mechanical parts purchased
- P.C. boards purchased
- P.C. boards single-sided, flow soldered
- P.C. boards, uniform hole spacing
- Electronic components purchased with pre-tinned leads
- Electronic component leads preformed
- Wires cut length, marked, mechanically dip-soldered
- Connectors purchased with pre-filled cups.

Further, the inspection plan upon which the estimates are based, assumes the following characteristics:

- 100 percent manufacturing inspection (visual)
- Sampling inspection of purchased parts
- Test equipment/tooling proofing in early releases

- Test equipment/tooling calibration and control
- Processes monitoring and control
- Operator training/certification
- Good commercial quality standards.

7.3 COST ESTIMATE

Estimates of approximate costs have been developed based on the schedules, quantities, and other assumptions defined in the preceding sections. This estimate, presented in Table 7-10 covers the FDMA mobile (Type I) configuration previously specified as the baseline.

This estimate includes:

- Design
- Tooling (and tool maintenance)
- Test equipment (and maintenance)
- Production planning/control
- Material planning/control
- Production (process) engineering support
- Production supervision
- Production testing
- Acceptance testing
- Inspection/QC
- Parts/materials - commercial level.

It should be noted that the baseline estimate detailed in Table 7-11 includes design costs of $215,000 amortized over the first 1,000 units. Amortization of these costs over the first 110 units will change the cost distribution as follows:

- The first 10 units will increase by approximately 47 percent
- The next 100 units will increase by approximately 20 percent
- The next 400 units will decrease by approximately 6 percent
- The next 600 units will decrease by approximately 6 percent.

Subsequent units will remain unchanged.

Table 7-10. Total Estimated Costs - FDMA, Type I Terminals (Estimate "A" - Baseline) (Costs in K$)

	Lot 1		Lot 2			Lot 3		Lot 4		Total
	Rel. 1	Rel. 2	Rel. 3	Rel. 4	Rel. 5	Rel. 6	Rel. 7	Rel. 8	Rel. 9	
No. of Deliverable Units	10	100	400	600	1000	2000	2000	2000	2000	10,110
Design	5	30	80	100						215
Parts and materials	21	210	660	990	1200	2400	2400	2400	2400	12,681
Management and supervision	35	100	100	100	150	150	150	150	150	1,085
Material/production control	8	35	80	100	120	150	150	150	150	943
Tooling and test equipment										
Tooling	10	20	25	30	35	35	35			190
Test equipment	20	40	40	40	50	60	60			310
Repair/ maintenance	2	5	5	5	7	10	10	15	15	74
Total	32	65	70	75	92	105	105	15	15	574
Mtg. engineering	10	30	20	20	20	10	10	10	10	140
Environ. test (sampling)	2	4	6	6	10	10	4	4	4	50
Assembly and test	10	58	137	165	275	550	550	550	550	2,84
Quality assurance	3	15	36	44	73	147	147	147	147	75
Attrition allowance	12	23	14	15	16	16	8	8	8	12
Total Cost	138	570	1,203	1,615	1,956	3,538	3,524	3,434	3,434	19,412
Unit Cost	13.8	5.7	3.0	2.7	1.9	1.8	1.8	1.7	1.7	1.9

7.4 DISCUSSION

The cost estimates include only those costs directly associated with manufacturing. This excludes the research and development and design costs necessary to bring a conceptual design up to a "breadboard" stage. These costs are a function of the design complexity, risk of the technology and many other factors. A rough comparison with other programs indicates that research and development cost for the present terminal units would be in the range of 2 to 4 million dollars. For the full 10,000 unit production run the added cost for R&D is therefore 200 to 400 dollars per unit. This is relatively small compared to other costs if a full 10,000 units is produced.

It is interesting to compare the estimated costs with other similar units. The Motorola MICOR radio single-frequency digital private line mobile radio (complete package) sells for about $1600 (Reference 3c). This unit provides one FM voice channel at 800 MHz and 35 watts RF power. The US Army Satellite Communication Agency Manpack Satellite Terminal AN/PSC-1 has a cost per unit of about $23,000 for 200 units. This unit provides up to 7000 voice channel frequencies at 225 400 MHz with selective call notification, digital voice and data capability (Reference 3b).

It is felt that the selected FDMA terminal complexity is between these two units, but probably closer to the military unit. Suppose we amortize an R&D cost of 2 million dollars over the first 110 units in Table 7-2 for a cost of $18,180 per unit or a total cost of $24.6K per unit for the first 110 units. This is slightly more than the 200 unit cost of the AN/PSC-1 because only 110 units were assumed. If the same number of units were produced then the selected FDMA terminal cost would be less than the AN/PSC-1. The selected FDMA terminal cost is slightly more than the commercial unit selling price. The explanation for this is that the FDMA terminal has additional order-wire and logic equipment. Furthermore, the commercial unit is produced in larger quantities, enabling LSI and automated assembly equipment to be used. Hence, it appears that the costs estimated above are the right order of magnitude.

7.5 SPACECRAFT COMPLEXITY AND COST

The PSCS Spacecraft (Reference 2) is being configured as a single launch on a shuttle-IUS. This launch vehicle presently in development has a specified payload capability of 5000 pounds (2268 kg) to synchronous orbit. Note that this is pure payload in that the IUS provides the apogee injection and can place the spacecraft in the desired attitude.

A spacecraft weight breakdown has been compiled based on existing spacecraft designs, future preliminary designs and considering the preliminary weight breakdown presented by NASA at the PSCS workshop given early in 1977. It is based on a tailored spacecraft rather than the NASA multi-mission module concept. This is shown in Table 7-11. It is based on the following assumptions:

1) The communications payload carries eight 100 watt and twelve 30 watt Ku-band TWTA chains. The overall weight is an extrapolation of TDRSS weights.

2) The antenna weights are based on the UHF antenna weights estimated earlier in the report and the Ku-band antennas are based on TDRSS antennas.

3) An allowance has been made for additional communications experiments including a 20/30 GHz SSTDMA experiment and a 41-43 GHz broadcast experiment.

4) Solar array assumes either a lightweight rigid or FRUSA at 30 watts/kg. without drives or deployment. The battery assumes 35 watt-hours/kg using Nickel-hydrogen batteries providing full eclipse capability.

5) Attitude control is a 3-axis system using skewed reaction wheels, a processor and standard earth and sun sensors. An RF sensor is added to provide antenna pointing accuracy of 0.05 degrees.

Table 7-11: Weight Breakdown

	Pounds	KG
Attitude Control (inc. RF Sensor)	200	91
Tracking, Telemetry & Command	120	54
Solar Array (3.5 KW)	300	136
Battery (Full Eclipse)	280	127
Converters/Power Control	100	45
Harness	120	54
Reaction Control (Dry)	120	54
Thermal/Structure/Integration	820	372
Communications Payload	600	272
Comm Experiments	200	91
UHF Antenna	100	45
K Antennas	200	91
Estimated Dry Weight	3160	1432
Margin (20%)	630	290
Maximum Allowable S/C Dry Weight	3790	1722
Hydrazine Propellant, Residuals & Pressurant	1000	450
S/C Gross Weight	4790	2172
IUS Adapter	210	96
IUS Capability into Synchronous Equatorial orbit	5000	2268

6) Tracking, Telemetry and command includes standard S-band which communicates at low data rate with either TDRSS or the ground.

7) Full 10 year north-south stationkeeping propellant is included using high performance electrically heated thrusters (Hipeht) at an average specific impulse of 300 seconds. Stationkeeping is not performed during the eclipse season and heater power is provided from the battery.

8) A thermal, structure, integration factor of 17 percent is used based on an average of recent spacecraft experience. It includes the weight for deployment and solar array booms.

The degree of spacecraft complexity would be in the same class as ATS-6, Intelsat V and TDRSS. Note that the TDRSS spacecraft is now being designed for a Shuttle-IUS launch only (the Atlas-Centaur version has been dropped) and hence provides a good starting point for the PSCS estimations.

A spacecraft program cost estimation for PSCS has been done utilizing known, fixed price bids from a number of recent programs. The recurring price (cost plus profit and incentives) is plotted in dollars per pound as a function of spacecraft dry weight in Figure 7-1. Note that these are for programs with some quantity of production and which reach their midpoint of expenditure in mid-1978. TDRSS and Intelsat V would fit this model.

Let us postulate a PSCS program which starts end of the third quarter of 1980 and has a first launch in 36 to 40 months. We would be estimating in mid-1982 dollars. Assume 2 flight spacecraft one of which is a refurbished prototype. Assuming a dry weight of 3800 pounds and the average of the two curves in Figure 7-1, a price of roughly 33 million dollars per spacecraft is estimated. This should be increased by roughly 20 percent to 40 million dollars because of the limited production.

Development or non-recurring costs have been estimated at 90 to 110 million dollars for this class of spacecraft including the cost of the prototype. A cost of 10 to 15 million dollars is allowed for prototype refurbishment. Hence, the PSCS program would cost roughly 150 million dollars in mid-1978 dollars. Using an inflation rate of seven percent per annum, the price is aproximately 200 million dollars in 1982 dollars.

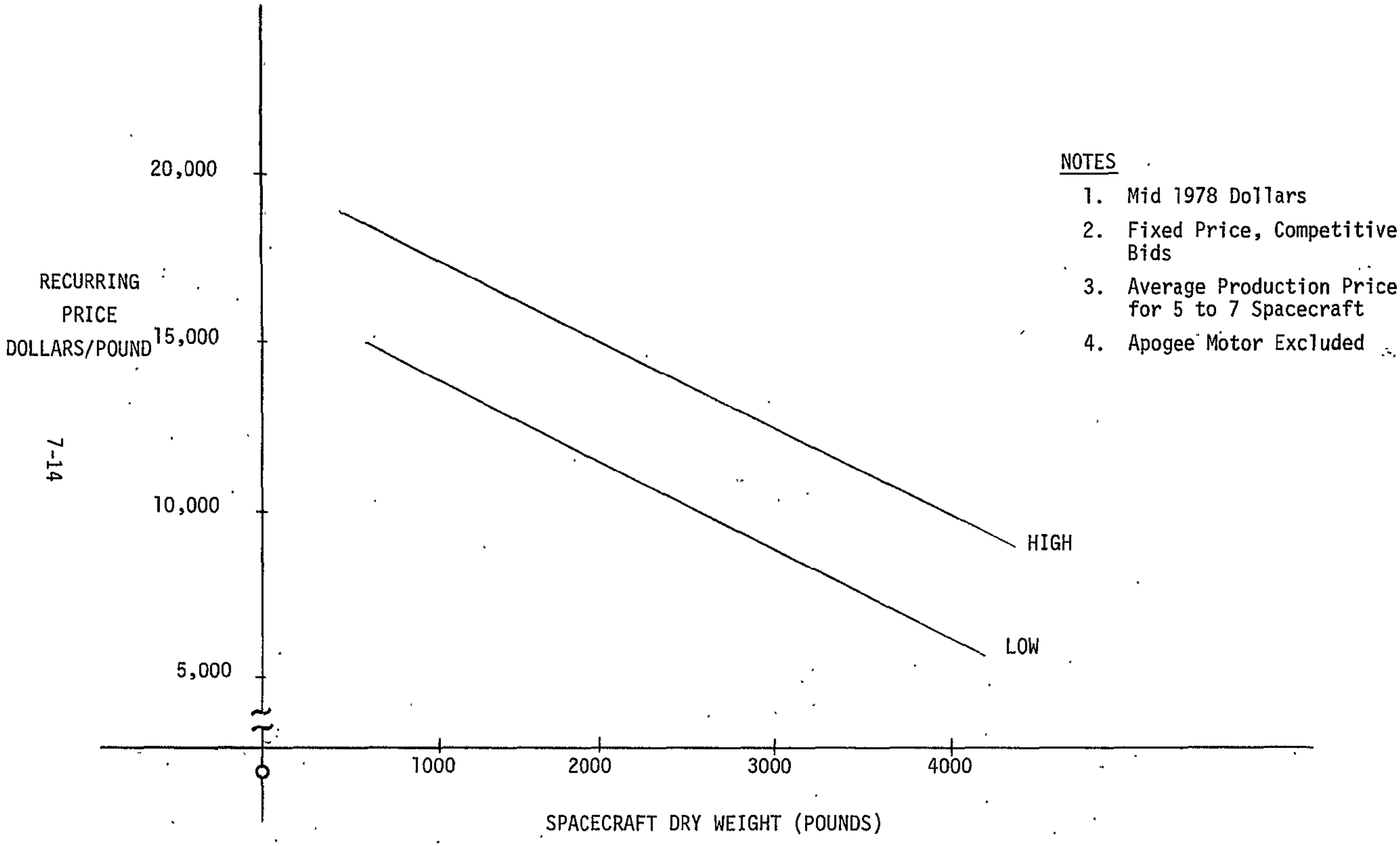


Figure 7-1. Spacecraft Recurring Price as a Function of Spacecraft Dry Weight

8. RECOMMENDATIONS FOR FURTHER INVESTIGATION

8.1 SYSTEM DESIGN

The analysis presented in the preceding sections has depended on a number of assumptions. Detailed performance evaluation will require determination of several key issues by further study. These issues include the following:

- System utilization
- Amount of radio frequency interference
- Need for multipath protection
- Use of new frequency bands
- Tolerable delay between channel request and channel assignment
- Need for jammer protection
- Need for privacy
- Downlink power budget
- Voice performance.

These issues are discussed in greater detail below.

System utilization is the key factor determining system design. The number of users, average usage per terminal, load distribution through the day, and data type (voice, fax, data), determine the number of channels required. The number of channel requests per terminal determines the loading on the orderwire and hence the multiple access design for the orderwire. The connectivity (local or long distance) determines the interzone coverage required.

The amount of radio frequency interference is important, particularly if certain portion of the spectrum contain significantly more interference than others. In the UHF region many powerful transmitters radiate. Any spillover of their energy into the band reserved for the MMACS will degrade performance. This is particularly important because terminal antennas will have an "omni" characteristic and the satellite antenna will cover the

entire contiguous United States. The other side of the coin is that the "broadcast" type signal will necessarily impinge on neighboring countries and may be a problem. The availability of spectrum in the UHF and L-Bands needs to be resolved also.

The type of multipath that is most likely to be a factor is that due to reflections from buildings. The degree to which this factor affects performance requires investigation for the ground mobile to space link.

The use of higher frequency bands, e.g., 12/14 GHz (Ku-Band) or 20/30 GHz, should be considered to avoid spectral crowding and interference at UHF. Development of narrowbeam ground antennas and high-power amplifiers is needed.

The acceptable delay between channel assignment and request determines the computation speed required to do the channel assignment processing. It also determines whether satellite or ground control of channel assignment is necessary. Finally, it determines the number of times that two requesting terminals can be allowed to have message collision on the orderwire. Delay of about 1 sec or more is required due to the round-trip delay and response time.

The amount of jammer protection required in the MMACS system depends on how critical the communication is and the likelihood of jamming. CDMA is very effective against a narrowband jammer. Therefore, if jamming protection is a major factor in evaluation of system performance CDMA will become an attractive approach.

The need for privacy is a complex issue. Varying degrees of privacy are possible. However, in a system with thousands of terminals and free space transmission, privacy from a determined listener with an electronics background requires significant increases in system complexity.

The downlink power budget can only support 100 voice channels even with use of voice activation and high-power transistors in a multi-beam antenna. To confidently achieve a 400 channel capacity will require larger

antennas (8-zone) and possible frequency reuse. Antenna study would be appropriate. It may be necessary to increase satellite transmitter power and reduce receiver noise figure. The constraint of not having a pointing antenna on the mobile is a weak link at present. Thus, automatically pointing antennas (electrical or inertial) are needed for increased capacity.

FM demodulator performance determines the SNR required at the receiver and hence the satellite power required. The SNR needed also depends on the voice quality required by the listener. Trained operators (Air Traffic Controllers) can achieve high word intelligibility at much lower SNR than is required for "good quality" voice transmission.

8.2 FUTURE DEVELOPMENTS

8.2.1 Spacecraft Design

A total spacecraft design is beyond the scope of future study in the context of the mobile service. This is due to the combination of the mobile service and Ku band television broadcast payload in the PSCS spacecraft. Hence, it is worthwhile to discuss some of the new spacecraft technology considerations for the mobile service.

8.2.1.1 Rf Amplifier

A CONUS coverage scheme requires a 300 watt linear power amplifier with narrow bandwidth at a center frequency of about 870 MHz. There is no existing space qualified device which comes close to this requirement. ATS-6 carries two solid state amplifiers with power outputs of 80 to 110 watts. However, these amplifiers operate class C and would produce intermodulation products which would be undesirable both in band and out of band.

There are a number of posssible candidates for the 300 watt amplifiers. These include solid state, electron bombarded semiconductor (EBS), a TWT or klystron and perhaps a vacuum tube triode.

A 300 watt solid state amplifier could be made up of six 50 watt amplifier modules; each module would be composed of 4 final stage transistors plus a driver. Each transistor would operate at about 15 watts output. The saturated rating of each transistor would be roughly 50-60 watts. The transistor manufacturers (CTC,TRW Semi and MSC) have devices in this power range.

The efficiency of this solid state amplifier would be about 29 percent from a regulated bus assuming that each device operates at 38 percent efficiency (based on FLTSATCOM results). This is probably optimistic considering that we are operating at 870 MHz rather than 240 MHz and that there are many more devices. If regulation losses are included, then a DC to rf efficiency of roughly 20 percent would be reasonable for the 300 watt solid state amplifier.

There are linearization techniques such as feed forward which might be applicable especially because of the narrow bandwidth. The question to be resolved is that of DC to rf efficiency, i.e., does the linearization reduce the efficiency below that obtainable operating in a linear mode?

NASA has been funding the development of an electron bombarded semiconductor (EBS) device at Watkins-Johnson for a number of years. This device is qualitatively a cross between a TWT and a semi-conductor and its operating mode is basically linear. Work started over 3 years ago on a 200 watt S-band device with a goal of 50 percent efficiency using 12 diodes. This effort culminated with only a single diode being illuminated and an operating efficiency of about 25 percent. The project has been restarted at L-band with a goal of 50 watts output using 4 diodes. A new matching network approach has been utilized. Clearly development efforts on the EBS would have to be accelerated if it is to be available for a program start within the next few years.

Inquiries with various manufacturers including Hughes, Litton, Watkins-Johnson and Varian have failed to uncover any existing TWT's or klystrons that might be adapted or any tubes under development. The manufacturers were uniformly discouraging and uninterested in the application.

A limited inquiry in the vacuum tube area has uncovered a planar triode made by G.E. in Owensboro, Kentucky that is of interest. A 100-watt tube operating in slightly backed off class C provides 40 percent efficiency, i.e., 500 volts at the plate drawing 0.5 amp. The gain is 9 to 10 db. The tube is used in a mono-carrier operation and G.E. has not run any tests to determine the intermodulation performance with multiple carriers. The tube is physically small, about 1 inch maximum dimension, rugged, runs at high temperature, and is cooled using heat sinks and radiation fins.

A basic problem is the relatively short life at design cathode loading. Life tests have successfully run 15,000 to 17,000 hours. G.E. estimates that it would be necessary to derate the tube to about 30 watts to increase the expected lifetime to the 7 to 10 year satellite requirement. Thus, compared with the solid state design requiring about 24 final stage devices, the vacuum tube design could conceivably be accomplished with 10 devices. The overall amplifier efficiency would probably be equivalent to that of the solid state amplifier.

8.2.1.2 Antenna

The key areas dictating antenna requirements include:

- Increased capacity by multizone operation
- Frequency range
- Reduction of interference outside CONUS
- Coverage of Hawaii, Alaska, Caribean.

A scheme for 8 zone coverage was shown in Section 5.2 with a capacity of 400 channels. Logical extensions of this to 16 zones and more are limited by antenna aperture, bandwidth available, and weight and power. For each doubling of the number of zones, the capacity can be quadrupled, assuming the gain is increased 3 db per zone by halving the area. Thus, for example, 16 zone system could provide 1600 channels. Frequency could be reused 4 times requiring a bandwidth of 10 MHz. Maximum aperture would be about 65 feet.

Future studies based on channel requirements should determine the practical limitations of system capacity based on an allocation of system weight for the mobile payload.

Multizone coverage clearly benefits interference reduction for Mexico and Canada since the CONUS contour is matched more closely by a set of multiple beams. In addition, antenna design techniques for reduction of sidelobe amplitude must be investigated to further enhance interference reduction.

Coverage of the Pacific Islands and possibly the Caribbean can be done with additional feeds for area or spot coverage.

8.2.2 Terminals

The terminal development issues include:

- Antenna for high-gain at UHF
- Microprocessor Command and Control of Order-Wire Signalling
- Use of Higher Power Amplifier
- Use of Ka Band (20 to 30 GHz).

These issues are discussed briefly below.

Since the mobile terminal must be operationally simple, a hand-pointed antenna is not feasible. This leaves electronically steered arrays and inertial pointing as candidates. Unfortunately, the required aperture size at UHF limits the gain achieved with a vehicle mounted antenna even assuming a pointing capability. The processing associated with electronically steered arrays usually requires a large ground station facility (e.g., TDRSS). The alternative of an inertially based pedestal that points a helix at a segment of the sky is possible. Mechanical costs would be high and reliability in the mobile environment could be low.

Command and control of the demand access function would determine the flexibility of the user terminal. A microprocessor chip could provide automatic channel selection and queueing, "call waiting" notification, monitoring and billing, and other commercial features similar to those contemplated for telephone electronic switching system. A microprocessor could also improve the multiple-access efficiency by automatically avoiding channels with high multipath or man-made interference. A very high "turn-over" rate for the multiple access channels could be achieved by rapid hand-over of temporarily unoccupied channels to new customers even if only for a few seconds.

Transistor manufacturers see rf power of 60 watts at UHF on the horizon. The achievement of 100 watts (class C) is more of a problem. Alternatively, high-power vacuum tubes could be used. Here again the heat problem would probably require forced-air cooling. The development of efficient power amplifiers in the 50 to 100 watt range is adequate for the mobile uplink. Power supply for the hand-held unit appears unlikely but this would be a good development area.

The use of Ka band has obvious advantages. Its great disadvantage is the increased path loss (about 26 db greater than UHF). This can be partly accounted for by using smaller "spot" beam antennas to cover CONUS. This of course increases spacecraft complexity and interbeam switching requirements. A great advantage of Ka band would be in the ground terminal antenna which could be developed as an automatic electronically steered array. Of course, the entire ground radio at Ka band (antenna, rf equipment, etc.) would be a development risk as no mobile terminals presently are contemplated at Ka band. The most important factors are: 1) small solid-state device power (<1 watt) at Ka band, and 2) presently very high costs of anything at Ka band.

Other areas associated with the terminal are:

- Privacy Mode
- Position Location
- Automatic Reporting

A level of privacy can be achieved through standard analog techniques already mentioned. Higher privacy levels are compatible with the FDMA design. For example, a digital voice signal can be mod-2 added to a nonlinear shift register sequence. Only receivers with the SR "key" could decode the transmission and the key could be changed periodically. Similarly, position location through triangulation from two or more satellites is possible from a terminal equipped with a coded "beacon". Automatic reporting of the terminal status (e.g., vehicle moving, door open, etc.) can be accomplished with simple sensors and an encoder.

9. CONCLUSIONS

A study of multiple access techniques (FDMA, CDMA, TDMA, SDMA) for mobile user application was performed. The communication capacity of FDMA, CDMA and TDMA was examined in detail with the following constraints:

- Limited bandwidth (less than 4 MHz)
- Limited power (less than 300 watts CONUS)
- Maximum capacity (up to 10,000 users)

The capacities of FDMA, TDMA and CDMA were compared on the basis of the number of equivalent voice channels that could be supported. It was found, for example, that FDMA required about seven times less RF bandwidth for the equivalent number of channels than CDMA, and that TDMA could support only about 80 percent of the number of channels that FDMA supports.

The implementation of the system was examined in detail. In the area of terminal complexity, as another example of the findings, it was found that the TDMA terminal required power would be about 700 watts to support the same communication quality as FDMA.

After consideration of the tradeoff analysis it was decided to select an FDMA system for further analysis. The use of a spatial diversity scheme (time-zone coverage via a 4-beam, 8-feed antenna) substantially improved the link (antenna gain and power amplifier) at no loss of multiple access capability. The selected system can support 100 equivalent voice channels in CONUS.

The terminal design was developed for FDMA, TDMA and CDMA terminals. The selected FDMA terminal was developed in various options (receive only, transmit and receive, transmit and receive with demand access) and various configurations (mobile, portable and hand-held).

The terminal provides the voice, data and facsimile communications as required in Table 1-1. In addition, the terminal has a demand-access capability. This capability is implemented via a separate data channel to a system control station. By random accessing this order-wire data channel the terminal can request use of a vacant channel or a dedicated channel assignment. The system accommodates a mix of demand-access and fixed-assignment terminals.

The terminal costs and spacecraft cost impact were estimated. Terminal costs were based on an estimated parts list cost and on a breakdown of manufacturing costs. The results are summarized in Section 7. Costs seem fairly comparable to similar units and are about $2,000 per unit for large production quantities.

Based on the foregoing brief look at a mobile communication system it appears that a medium-sized system is feasible with low-risk technology at a reasonable cost (relative to commercial mobile units). The system is expandable and potentially very efficient for multiple demand access with the built-in order wire scheme. A detailed system design of the selected FDMA spacecraft and terminal and demand access techniques and investigation of the key engineering areas that were pointed out in Section 8 is recommended as a next step in this study.

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